Science of Venus environment in 21st century

Takeshi Imamura (ISAS/JAXA)

Venus is a key planet for better understanding the mechanism of the differentiation of the planetary environment. Major scientific issues are classified as:

1. Climate system and stability
   - Cloud amount and high albedo
   - Superrotation
   - Volcanism and atmospheric escape
2. Climate evolution
   - Ancient Venus
   - History of water

ESA's Venus Express covers broad science topics and found new features including: high-altitude enhancement of SO an SO_2, high-altitude enhancement of D/H ratio, long-term variation of SO_2 mixing ratio, radio bursts from lightning, detailed structure of polar dipole, and possible detection of active volcanism. JAXA's Akatsuki will explore the global-scale dynamics of Venus. In spite of these achievements, most of the fundamental questions raised so far on the Venusian climate are left unsolved. Specifically, the chemical and dynamical processes that control cloud formation and the stability of atmospheric composition are still unclear. This is firstly attributed to the lack of observations of key radicals driving catalytic cycles such as ClO and HO_2 and key reservoirs such as HCl and $ClONO_2$. The abundance O_2, which determines the ways of the oxidation of SO_2 to H_2SO_4 (main component of clouds) and the reduction to S_x (possible condensation nuclei for cloud formation), is also unknown. The fluid dynamics that exchange air between the photochemically-driven upper atmosphere and the thermochemically-driven lower atmosphere across clouds are also key processes controlling the atmospheric composition and cloud formation.

A future Venus orbiter mission focusing on the climate system is under discussion. The goal of the mission will be to understand photochemistry, cloud physics and vertical transport processes inside and above clouds. Satellite-to-satellite radio occultation using a sub-satellite enables three-dimensional observations of the temperature field and the H_2SO_4 vapor distribution. Data assimilation using those temperatures and numerical models would allow reproduction of the four-dimensional dynamical field. A sub-millimeter sounder measures abundances of key trace gases both in limb- and nadir-viewing geometry. We also consider studies of atmospheric escape based on the observation of the composition in the lower thermosphere by the sub-millimeter sounder and the observation of the three-dimensional ionospheric density by satellite-to-satellite radio occultation, together with in-situ observations of escaping species.

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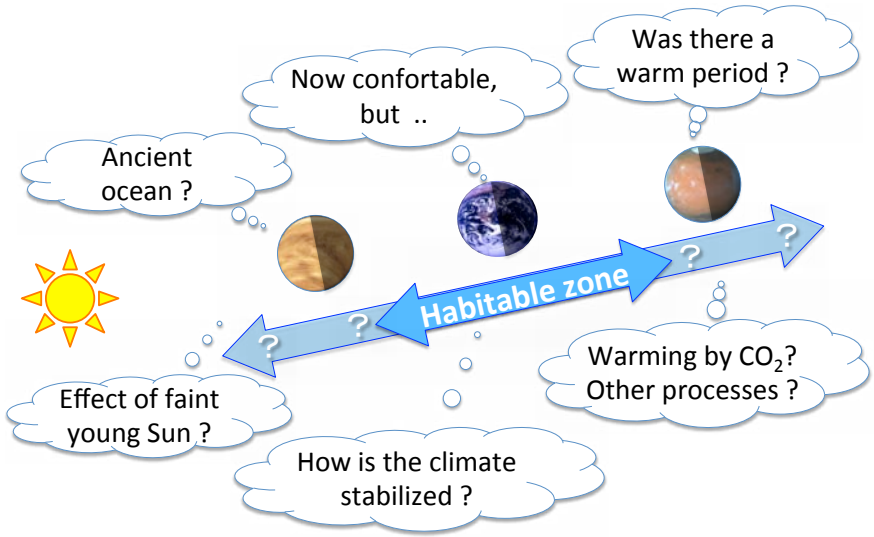
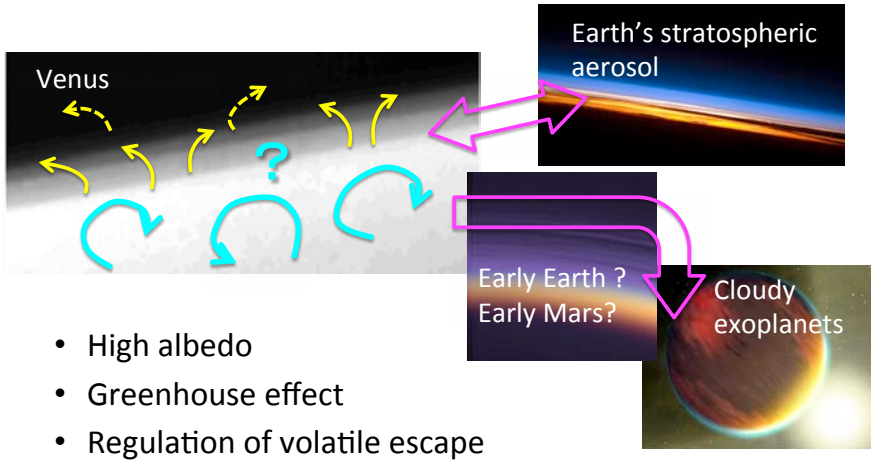
Venus : inner edge of 'habitable zone'

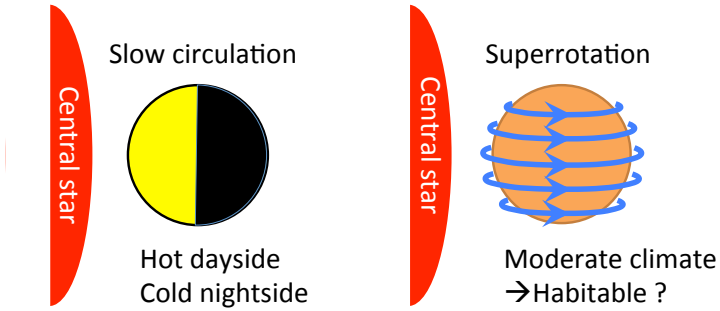


Venus : Reference aerosol atmosphere



- High albedo
- Greenhouse effect
- Regulation of volatile escape

Venus : an extreme of atmospheric circulation



- Tidally-locked planets are slow rotators like Venus. Superrotation can redistribute energy between the permanent dayside and the permanent nightside, otherwise the plant could have a hostile environment.
- Is superrotation ubiquitous in the universe ?

Major scientific issues

- Climate system and stability
  - Cloud amount and high albedo
  - Superrotation
  - Volcanism and atmospheric escape
- Climate evolution
  - Ancient Venus
  - History of water

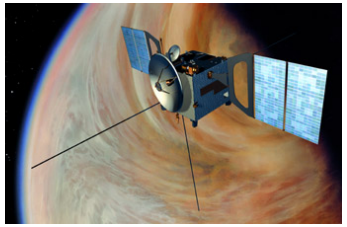
→Unified understanding of planetary environments in and outside the solar system

Personal interest

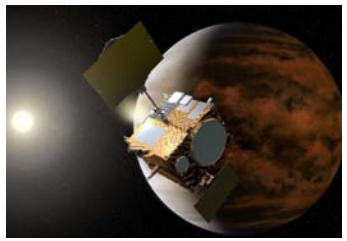
- How can clouds form in the atmosphere where condensation nuclei of surface origin should be absent ? Can clouds form on any planet having condensable gases ?
- Did superrotation exist throughout the Venusian history irrespective of the presence of H_2SO_4 clouds and CO_2 atmosphere ? How did it control the albedo of ancient Venus ?

Two missions in 21th century

1. **Venus Express** (2006-2014)



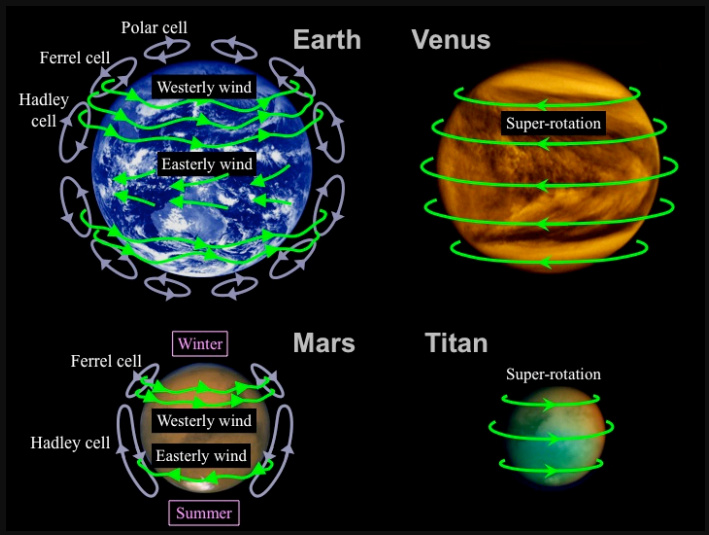
2. **Akatsuki** (Arrival in Dec. 2015)

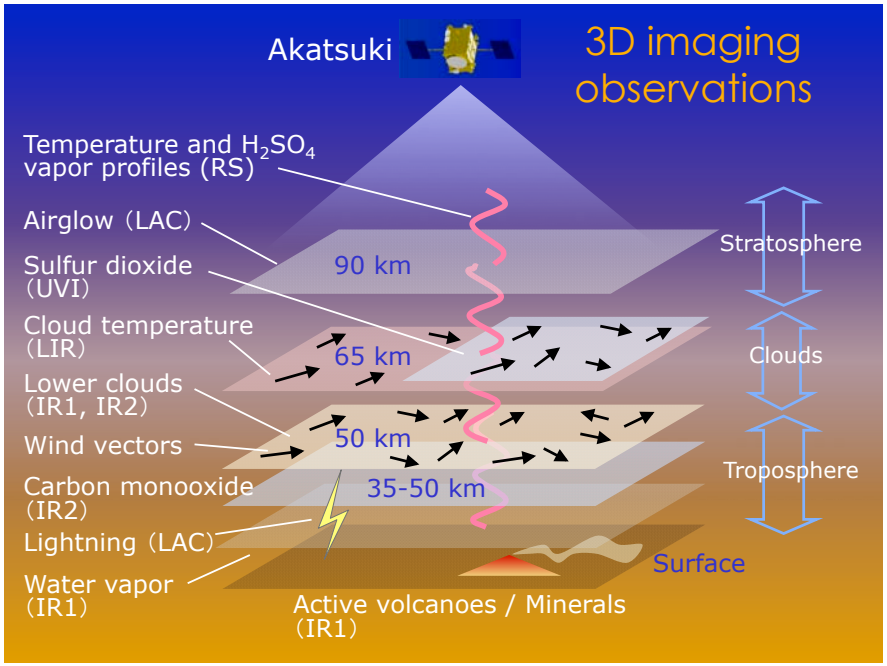


Two missions - expected achievements

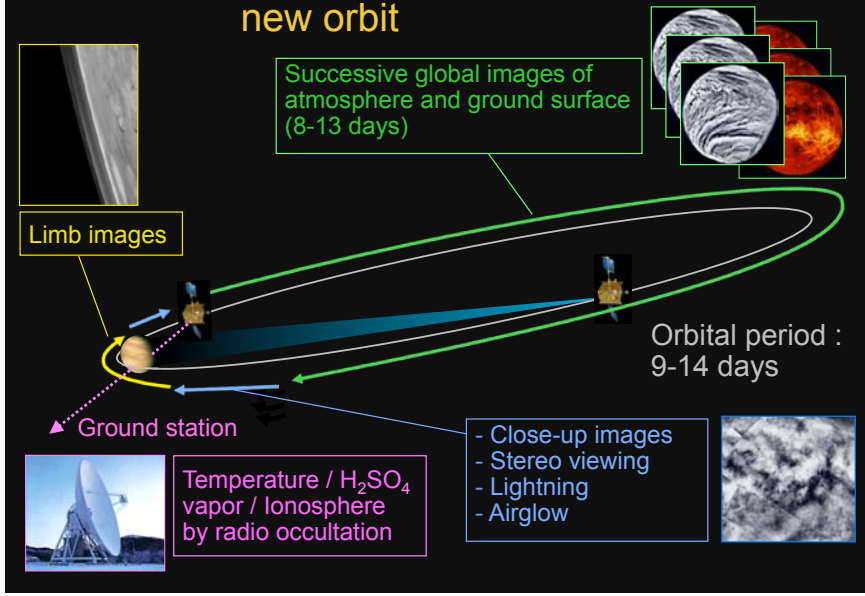
1. **Venus Express**
   - Covering broad science topics
   - New features: high-altitude enhancement of SO an SO_2, high-altitude enhancement of D/H ratio, long-term variation of SO_2 mixing ratio, radio bursts from lightning, detailed structure of polar dipole, possible detection of active volcanism ..
2. **Akatsuki**
   - 3-D fluid dynamics using multi-wavelength imaging
   - Optical detection of lightning

Akatsuki : Venus mission for comparative planetary meteorology

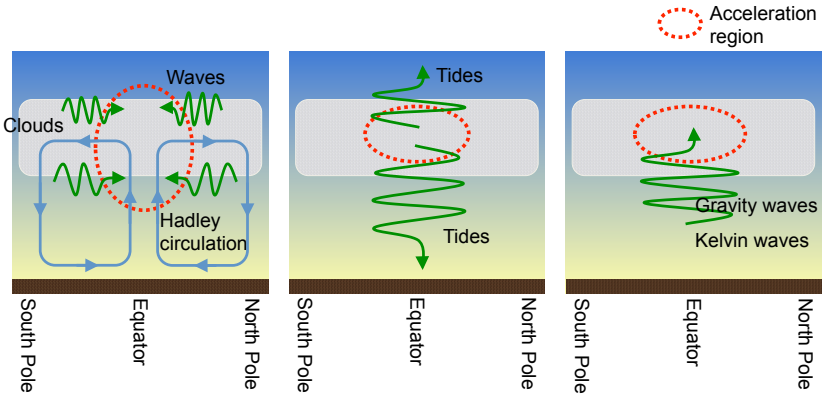




Observation plan based on the new orbit



Identification of key processes sustaining the super-rotation using 3D meteorological data

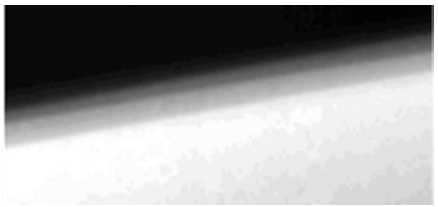


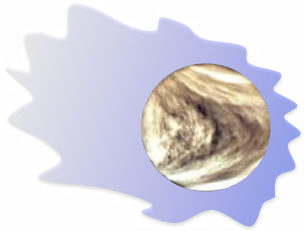
Major issues still remain unsolved ..

- Mechanisms sustaining the current climate
  - Chemical cycles controlling H_2SO_4 production and atmospheric composition
  - Cloud physics controlling the cloud amount and the planetary albedo
  - Volcanic activity and atmospheric escape controlling atmospheric composition
- The mechanisms need to be understood to extrapolate the knowledge about Venus into terrestrial planets in general.

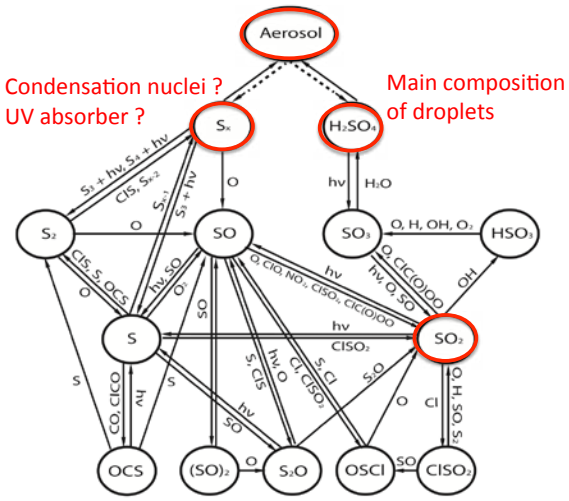
Photochemistry on Venus

- Abundant S and Cl, resulting from the absence of ocean, drive various catalytic reactions.
- Catalytic cycles produce aerosols, and stabilize CO_2 atmosphere against photo-dissociation.
- Hydrogen escape occurs via photochemical formation of H, H_2 and HCl and the subsequent upward diffusion in the thermosphere.



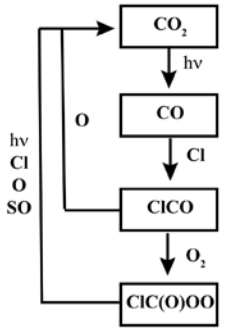


Sulfur cycle on Venus

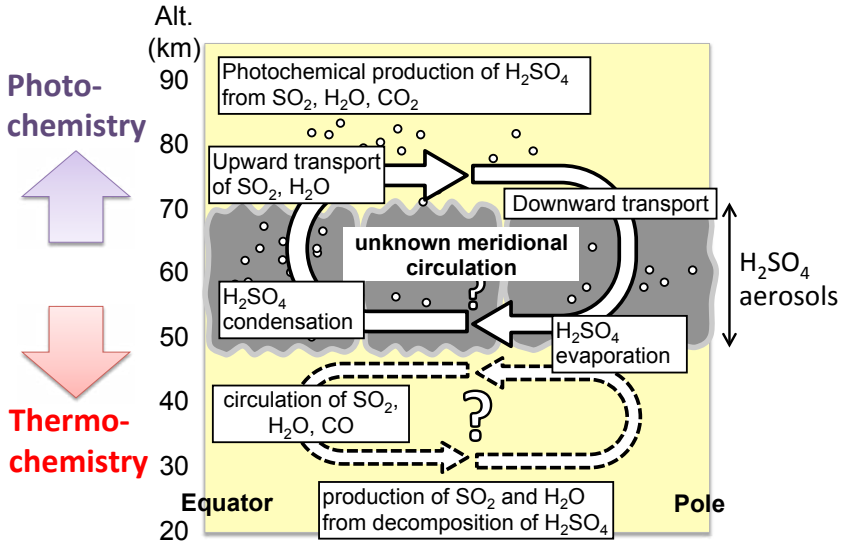


Zhang et al. (2012)

CO_2 stabilization



Mills et al. (2007)



Clouds form through material exchange between the two different atmospheric regions

Problems of Venus's atmospheric chemistry and aerosol physics

- Chemical paths to produce H_2SO_4 and condensation nuclei (S_x ?) are unknown.
  - Lack of observations of the key radicals driving catalytic cycles such as ClO and HO_2 and the key reservoirs such as HCl and $ClONO_2$
  - Lack of observations of O_2, which determines the ways of the oxidation of SO_2 to H_2SO_4 and the reduction to S_x
  - The high-altitude enhancements of SO and SO_2 discovered by Venus Express cannot be explained.
- Vertical circulation between the photochemistry-driven upper atmosphere and the thermochemistry-driven lower atmosphere is unknown

Future missions ?

- Direct observations of atmospheric composition and surface material using landers and balloons are absolutely needed for unambiguously identifying the aerosol composition and the surface material, measuring isotopic ratios, and searching for evidence of ancient ocean.
- Orbiter missions observing the atmosphere globally in 3-D are also needed.

An atmospheric orbiter concept

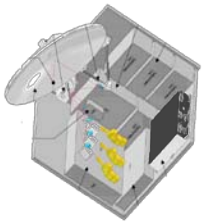
(Discussion with H. Ando, T. Iwata, A. Yamazaki, Y. Kasan, H. Sagawa)

- **Goals:** Unambiguously identifying the photochemistry, cloud physics and vertical transport inside and above clouds that sustain the climate system
- **Instruments**
  - **Sub-millimeter sounder** : 3D distributions and temporal variations of key species (O_2, O_3, ClO, HCl, SO, SO_2, OCS, ClC(O)OO, $ClONO_2$, CO, H_2O, HO_2,..)
  - **Sub-satellite** : Satellite-to-satellite radio occultation for 3D observations of temperature, H_2SO_4 vapor and electron density
  - UV and IR camera
  - IR spectrometer

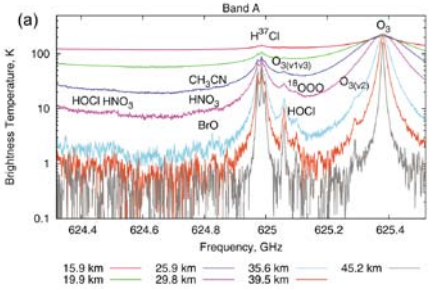
Sub-millimeter sounder

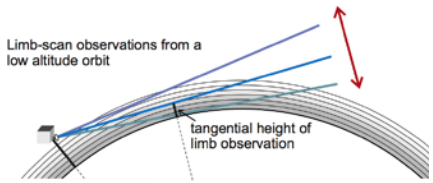
Spectroscopy of rotational lines

- 3D distribution of trace gases
- 3D distribution of temperature
- Doppler measurement of wind velocity



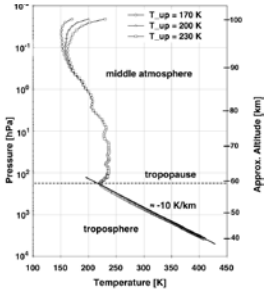
A model for Mars orbiter
(Courtesy: Kasai@NICT)





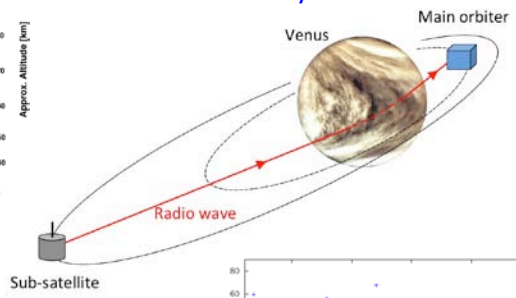
Spectra of Earth's atmosphere taken by SMILES onboard ISS (Kikuchi et al. 2010)

Satellite-to-satellite radio occultation

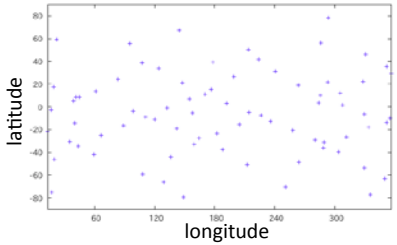


Tellmann et al. (2009)

3-D distributions of temperature, H_2SO_4 vapor and electron density

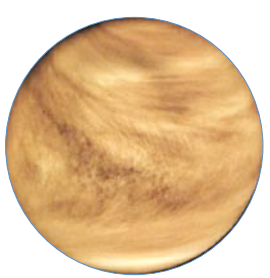


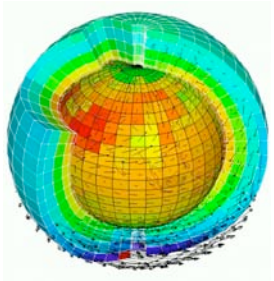
An example of the distribution of observation points in four days in the coordinate system rotating with the super-rotation (calculation by H. Ando)



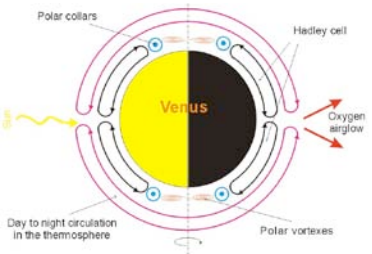
Understanding the material circulation

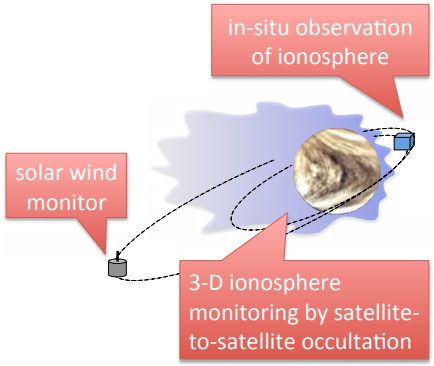
- Data assimilation using 3-D temperatures and numerical models allows reproduction of 4-D dynamical field.
- Through development of chemical transport models using the assimilated meteorological field and the observed trace gas distributions, the chemical and thermal equilibrium of Venus atmosphere will be understood.





Thermospheric circulation and atmospheric escape





Sub-millimeter sounding upto the lower thermosphere, combined with plasma measurements, reveals key atmospheric processes regulating escaping species.

Summary

- Venus is a key planet for better understanding the mechanism of the differentiation of the planetary environment.
- Although Venus Express has revealed various new features of the planet, most of the mechanisms sustaining the Venus environment are still unclear. Akatsuki's research is mostly limited to global-scale dynamics. The goal of the Venus's environmental science in this century will be to understand all key processes and extrapolate the knowledge into Earth, Mars and extrasolar terrestrial planets.
- A future Venus orbiter mission focusing on cloud physics and atmospheric chemistry is under discussion. The primary mission payloads will be a sub-millimeter sounder and a sub-satellite.