**Venus Dynamic Tracer (VdT)**

**Theme**

Tracing "air motion" from "atmospheric ocean" to the thermosphere to understand **3D dynamics** of the Venus atmosphere

**Aim**

The Venus Dynamic Tracer (VdT) mission aims to understand the driving mechanism of the Venus atmospheric dynamics: how its momentum and energy including heat are transferred three dimensionally in the critical regions where many forces are acting. Although the super-rotation has been studied intensively, its coupling with actual vertical and meridional circulation, if any, is not clea. Also the relation with the ion dynamics, i.e., how much ion motion influence the neutral motion and vice versa, is another unknown question. Answering these questions requires measurement of the motion of air parcel (wind) and temperature in the lower part of the cloud and in the thermosphere where ions start to play role in the atmospheric motion.

**1. Scientific goal of the mission**

Venus is the closest planet to the Earth in both physical distance and size among the solar system bodies, and therefore Venus and the Earth are often called as twin planets. However, the present environment is quite different between these planets, making Mars, a little brother, more close to the Earth than Venus in terms of habitability environment (particularly temperature) on the planet. Unfortunately, how and how much different between Venus and the Earth or Mars has not been well understood compared to the Mars-Earth difference, mainly due to the thick cloud and high surface temperature. The former makes remote sensing observation difficult from the subsurface to the cloud layer up to 60 km altitude even with UV and LIR cameras, whereas the latter makes study by rovers impossible with existing technology. These difficulties made Venus much less understood than Mars. This problem still continues to today.

With 0.1-3 bar and 250 to 350 K (-20°C to +80°C) environment, the cloud layer 50-60 km altitude in the equatorial region and 47-57 km altitude in the polar region has similar pressure and temperature as the Earth's troposphere, and might even be habitable except its high acidity. In other words, Venus atmosphere, rather than the surface, is an astrobiology target instead of the surface. This applies even to exoplanets similar to Venus (exo-Venus). The

There have been many missions to Venus: Venera series, Vega-1, Vega-2, Pioneer Venus Orbiter (PVO), Magellan, Venus Express (VEX), Akatsuki, and many flybys. Among those, Vega. VEX and Akatsuki has revealed many dynamics and chemistry in the atmosphere inside and below the cloud layer below 70 km altitude. Furthermore, future missions (both approved and planned) investigate all possible atmospheric chemistry with probes, orbiter, and single balloon. Even some dynamics will be investigated by a balloon. However, they still cannot answer investigate key driving mechanisms of the atmospheric dynamics in the critical regions: lower cloud layer and thermosphere. These important questions are summarized in the following way.

**1.1. Unsolved issue 1: 3D-dynamics in the lower cloud layer**

**"** **What is the 3D dynamics in critical region at 40-60 km (main dynamics zone)?" (exact wording TBD)**

In the atmospheric dynamics, distinction between wave, circulation, eddies and shears are key elements. Akatsuki observations found many signatures of these dynamics, without able to distinguishing them particularly below 60 km where the camera sensitivity was low. Since the cloud layer is the most "newly heated" region in the atmosphere by absorbing the solar radiation, we also expect many dynamic features takes place. While most of the upward convection (driving region) is located near the equator, the actual circulation is determined where and how this lifted air parcel shinks during its meridional circulation.

*1.1.1. Dynamic related to Super rotation (or "distinction of circulation from waves")*

" What are actual roles of circulation and waves in maintaining the super rotation?"

The present understanding of the atmospheric dynamics is largely coming from VEX, Akatsuki and old Vega's balloons (plus Venus Express). They revealed the zero-order motion, i.e., super rotation and related gravity wave in the cloud layer. Akatsuki's optical observation suggests that thermal tides with the assist gravity waves are the main driver (Horinuchi et al., 2020), like a piston (=tide) rotating a wheel through a crankshaft (=wave). This scenario means that, but integrating the wave effect over the altitude, the energy and momentum are basically transferred within 2D plan in the horizontal direction.

However this scenario does not include the 3rd dimension, i.e., vertical motion and the meridian circulation (e.g., Hadley cell). It is unclear if and how much these motions contribute in maintaining the super rotation. Global Circulation Model (GCM) that is made specifically for the Venus environment predicts that both the gravity wave and the meridian convection assist the thermal tide to cause the super rotation (Sugimoto et al., 2019).

To understand the role of circulation, we first need to be able to separate it from the other dynamics such as waves. To distinguish, we need to clear two obstacles. One is detection of vertical motion of the air parcel, and the other is distinction such vertical motion from waves or simple fluctuation of horizontal flow.

For detection of the vertical motion, we need in-situ measurements in the atmosphere because Doppler shift method works well only when the signal from the object is strong. Therefore, even Akatsuki could not separate detect the vertical motion because the camera from the orbiter is taking 2D picture.

It is also difficult extract the vertical motion from the cloud morphology because of camera resolution. Even the north-south motion is not completely deduced from the orbiter's cameras because we cannot always distinguish any "horizontal motion of cloud" between actual circulation and wave propagation. At present, the motion of cloud observed camera is often assumed to be motion of the cloud for irregular patterns, and waves for regular patterns, but reality can easily be different or mixture of them.

Therefore we have to relay on in-site measurements by atmospheric probes and particularly balloons. Using Doppler shift of transmission from the Balloons, Venera probe obtained vertical speed of < 1 m/s (Kerzhanovich and Marov 1983). However, they cloud not identify if it is wave-like disturbance or actual convection/eddy because landing prove does not follow the air parcel.

Balloons have extra advantage by following the air parcel. Vega balloons obtained the vertical motion at 53 km altitude, fluctuating at ±3 m/s (Blamont et al., 1986; Linkin et al., 1986). However, without simultaneous measurement from the orbiter, it was not possible to distinguish between the convection or simple fluctuation of the super rotation with 70 km/s during these observations. To distinguish it, we need balloons at different altitudes and monitoring of the signal pattern from the orbiter.

*1.1.2. Other dynamics unique to Venus*

"How are the unique dynamics (shear, eddy, wave) other than super rotation: their relation to the super rotation, and any similarly to or essential difference from the Earth?"

The super-rotation makes the Venus atmospheric dynamics quite different from that of the Earth. However the uniqueness of the Venus dynamics is not limited to the super rotation. VEX and Akatsuki found many unexpected features in addition to the detailed morphology of the super rotation and large-scale dynamics related to the super rotation: (A) Short wavelength gravity wave at 65–70 km (Piccialli et al. 2014); (B) Long wavelength gravity wave at 45–50 km (Peralta et al. 2008); (C) Planetary-scale rounded wave (Peralta et al. 2007): mountain-induced stationary structure from north polar region to south polar region at 65-70 km altitude (Fukuhara et al., 2017), and north-south streak structure (Kashimura et al). For (A) and (C), the features are expected to be extend toward the lower altitude but difficult to confirm without in-situ balloons.

They could be related to the super rotation or they could be unique to Venus condition (location of the solar energy absorption, themodynamics that is strongly regulated to the chemical composition, very slow planetary motion, etc). To understand it, we again need to separate these unexpected dynamics into the wave-like motion, circulation, and shears. In addition, we expect more dynamics and waves at altitude there LIR and UV camera could not reach, and also dynamics that is contaminated by the super rotation.

At present strong convection layer is expected at 50-55 km altitude but this is from theoretical one obtained from the temperature gradient together and the predicted velocity is only order of \*\*\* m/s, which is very difficult to distinguish from one balloon only, particularly when it is one the fast flow.

Since the temperature gradient is larges between 50 km and 55 km at low latitude and slightly lower at high latitude, **at least one balloon should be placed at 50-55 km range** where the atmosphere is expected to be most unstable. On the Earth, driving energy source of circulations is normally located below unstable region, and hence we expect the same. Akatsuki NIR observation suggested the same. Therefore, **the second (and if possible third) balloon at lower latitude** would definitely give us how the atmospheric motion is coupled (or independent) in the vertical direction. Here, direct comparison of balloons and remote sensing is also inevitable to separate special-temporal structures.

*1.1.3. Thermodynamics*

"Is air parcel stable and unstable during its motion?"

To distinguish the convection and wave, i.e., instability of the air parcel, thermodynamics of the air parcel is important. This means that we have to trace the temperature and press with as light balloons as possible that can react the wind quickly.

*(combine with 1.1.1 or 1.1.2 or 1.1.3)? Validity of Venus GCM*

" Does Venus GCM represent actual Venus atmospheric dynamics?

Once we obtain and separate the circulation, wave, eddy, and shear flow, we can improve the Venus GCM. Having reliable GCM for both the Earth and Venus, one can have better GCM for different objects, such as past and future terrestrial conditions.

**1.2. Relation to plasma dynamics**

**"What is the relation between the neutral dynamic and ion dynamics?"**

In the thermosphere where molecules are started to ionized, ions starts to behave differently from the neutral atmosphere because they are sensitive to the electric field and magnetic field. Even without intrinsic global magnetic field on Venus, solar wind induces magnetic field and electric field to the thermosphere. In addition, the absorption of the solar energy is different between ions and neutrals. Tracing these motions give hint to understand the "entire circulation of the atmosphere" and "local ion-neutral interaction processes"

*1.2.1. Large-scale neutral dynamics in the thermosphere*

"How much is neutral circulation influenced by existence of ions: large-scale consequences?"

Neutral wind velocity at around 100 km (start of ionosphere) is typically in the range 100–300 m/s, stronger at the evening than the morning (Limaye and Rengel, 2013). However, we do not know the morphology at higher altitude where ionization rate is high. The ion velocity obtained by PVO and VEX indicates the same dawn-dusk asymmetry of the anti-sunward flow, but with velocity much higher (one order of magnitude). If ion and neutral are coupled, like the Earth thermosphere, neutral wind must be strongly affected.

On the Earth, the neutral dynamics in the thermosphere is driven by thermal convection by the Sun in the sunlit hemisphere and Joule heating of plasma in nightside polar region. However, in the nightside polar cap where the plasma motion that is originally driven by the solar wind drags the neutral atmosphere. Thus three different mechanisms is working. We do not know or even any hint how is this in Venus.

To understand it we need direct measurement of both neutral wind and ion wind in the region where ion density is comparable to the neutral density within order of magnitude (<180 km). Occasional dive to such low altitude is possible because VEX achieved a dive down to 135 km.

*1.2.2. Ion-neutral interaction in real space*

"How and how much does the ion-neutral coupling work in the real thermosphere?"

Inversely, ion motions are influenced by the neutral wind. To understand and generalize the relation between the ion drift and neutral wind in the thermosphere, we need the average effect in both direction (from ion to neutral and neutral to ion). Such knowledge, namely ion-neutral interaction, is a fundamental information to understand all planets and many objects in the Solar System, but it is not possible to measure in laboratories because of low density and low energy of these ions and neutrals (Yamauchi et al., white paper input to ESA, 2019).

**1.4 Methodology**

Balloon motion including P and T are obviously important. As the reference as well as understanding the balloons motion in the context of global dynamics in the horizontal direction, camera(s) are necessary. As bonus if mass budget allows, camera would be useful to monitor the cloud from the below and the surface for relative location identification, while infrasound is another useful measurement super rotation and related disturbance is expected to generate the infrasound signature that is reaching at long distance.

For the thermospheric part, we need to identify the mass flux and motions of ions and neutrals.

*Where to deploy balloons?*

* *All balloons must be deployed with single entry module (penetrator)*
* *Low-latitude (<20°) or high latitude (>60°)*
* *meridional convection where super rotation start to decrease (at shear), or mot heated region that drives many waves and eddies?*

*All balloons need determination of location*

* *Radio link between balloons and to the orbiter at same time for triangulation*

*Which altitude*

* *40-60 km altitude – one at 50-55 km*
* *Two balloons need T, P, transmission system, and one balloon with extra payload*

*Can we have 3rd and 4th balloons at different altitude without payload except radio link?*

* *This gives better determination of the position through inter-balloon triangulation*
* *If it survive more than 6 month (use N2 instead of He?), the Earth telescope may detect*

*What could be extra payload?*

* *Wind/inertia*
* *Infrasound (~200g?) = bonus?*
* *heat flux measurement*
* *Public camera*

**1.5. Required observations and strawman payload**

Table 1a. Measurement requirements versus science questions: Balloon

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| balloon payload | mass | 1.1.1 | 1.1.2 | 1.1.3 | 1.1.4 | 1.2.1 | 1.2.2 |
| UHF antenna system (Balloon location)  location <50 m (ideally <10m) accuracy |  | x | x | x | x |  |  |
| inter-balloon communication system  location <10m or <0.01% accuracy |  | x | x | x | x |  |  |
| Balloon T |  | (x) | (x) | x | (x) |  |  |
| Balloon P |  | (x) | (x) | x | (x) |  |  |
| 1-balloon: wind |  | x | x | x | x |  |  |
| 1-balloon: IMU |  | x | x | x | x |  |  |
| 1-balloon: Infrasound |  | x |  | (x) | (x) |  |  |
| 1-balloon: cloud camera (simple one) |  | (x) | (x) | (x) | (x) |  |  |
| option: aerozol or humidity ? |  |  |  |  |  |  |  |
| option: heat flux measurement ? |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
| two extra balloons (no payload) |  | x | x | x | x |  |  |

Table 1b. Measurement requirements versus science questions: Orbiter

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| orbiter payload | mass | 1.1.1 | 1.1.2 | 1.1.3 | 1.1.4 | 1.2.1 | 1.2.2 |
| Balloon location (equipment at orbiter) |  | x | x | x | x |  |  |
| Imaging (NIR1) | camera total  < 30 kg | x | x | (x) | x |  |  |
| Imaging (NIR2) | x | x | (x) | x |  |  |
| Imaging (LIR) > 60 km | (x) | (x) |  | (x) |  |  |
| Visual Monitoring | 0.3 kg | (x) | (x) |  |  |  |  |
| total inertia of wind / wind | 5-10 kg |  |  |  |  | x | x |
| Ion velocity | < 5 kg |  |  |  |  | x | x |

**Observation summary (old version 2022-0131)**

Multiple small balloons at 2-3 different altitudes (35-60 km) and at 2-3 different latitudes including the polar region are deployed.

Balloon payload is only radiosonde-type (P, T, wind speed, radio equipment for telemetry and positioning relative to the orbiter. Minimum or no "commanding").

Altitudes of the balloons are adjusted by adding extra payload mass, e.g., infrasound & IMU (Inertial Measurement Unit), for lowest altitude ones.

To make the balloons to survive long (target 120 days), we use N2 gas if possible, because the N2 gas does not easily leak through the skin unlike the He gas..

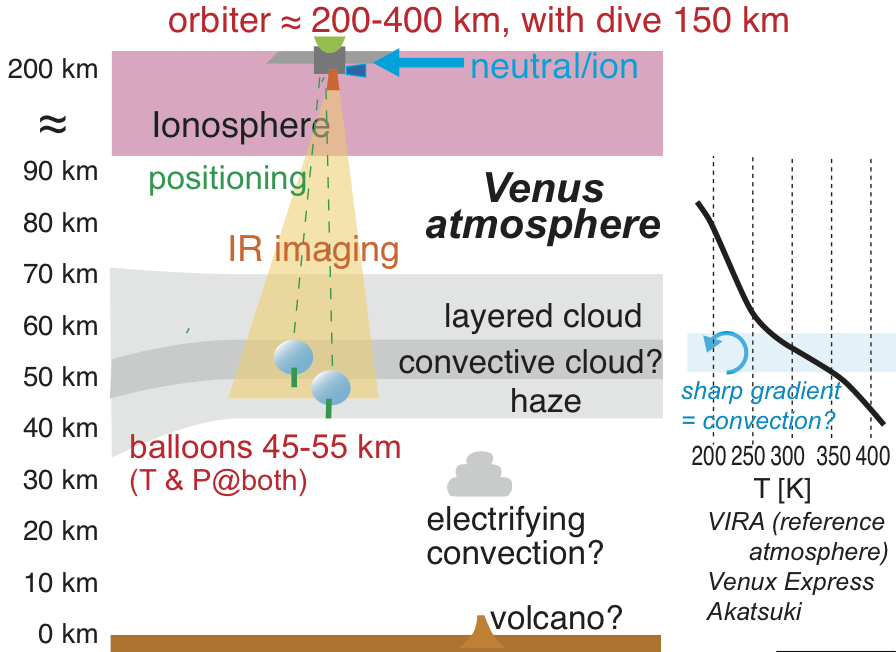
The radio-transmission from these balloons to the orbiter is also used for radio occultation and Doppler shift measurements, to obtain the integrated effect of temperature and vertical velocity over the altitude.

Orbiter measures neutral wind and ion drift velocity at as low altitude as possible (≤200 km).

Orbiter also has camera(s) to monitor the cloud motion and confirming balloon motions, if mission budget is allowed.

The low-altitude orbit ends after the nominal operation (4 month period when some balloons are floating), and change its altitudes to survive longer period as "extended mission period".

As an option, both He balloons (quick descend from high altitude) and N2 balloons (slow descend fro low-altitude) are mixed to change of altitude range.

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**2. Mission configuration**

**2.1. Mission profile (incl. balloons)**

2.1.1. Balloons (deployment)

2.1.2. Orbiter (orbit)

2.1.3. Communication

**2.2. Payload/instrument configulation**

**(incl. mass and power)**

2.2.1. Payload provision

2.2.2. Cost and funding

2.2.3. Schedule flexibility

2.2.4. Technology readiness level (TRL)

2.2.5. Mission profile and duration

**2.3. Technology**

**2.4. balloons (within ESA budget)**

**2.5. Attitude control**

**2.6. Venus environment**

**2.7. Planetary protection**

**3. Management and collaboration**

**3.1. Potential management structure**

**3.2. Payload consortium composition/funding**

**3.3. International collaboration**

**Core Hardware**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **instrument** | **name** | **organization** | **country** | **funding** |
| **(1) Balloon consortium** | | | | |
| co-PI for balloon specification |  |  | France | CNES |
| co-PI for tracing |  |  |  |  |
| co-PI fpr basic measurements |  |  |  |  |
| co-PI for extra measurements |  |  |  |  |
| co-PI for radio occultation |  |  |  |  |
| **(2) Camera from orbiter** | | | | |
| co-PI for IR-1 |  |  |  |  |
| co-PI for IR-2 |  |  | Belgium | BELSPO |
| **(3) In-situ at orbiter** | | | | |
| co-PI for ion (& neutral) velocity | Shimoyama | IRF | Sweden | SNSA |
| co-PI for accelerometer |  |  |  |  |

IRF: Swedish Institute of Space Physics, LTU: Lulea University of Technology

Mass estimate (inside parenthesis is margin)

|  |  |
| --- | --- |
| Element | mass (kg) |
| Balloons | 150 (+45) |
| orbiter (ballon related) | 25 (+10) |
| orbiter (other payload) | 55 (+15) |
| dry mass (\*1) | 1050 (+300) |
| Fuel (Xe) | 750 |

\*1: With small payload on orbiter (90 kg including instrument related to orbiter), orbiter is not very much heavier than Venus Express (700 kg). Instead, we ask more fuel (750 kg instead of 600 kg) to keep low altitude orbit.

Cost estimate for 2-year nominal operation

|  |  |
| --- | --- |
| Element | cost (Meur) |
| Balloon | 60-100 (\*1) |
| Other space segment | 130 (\*2) |
| Launch (16%) | 90 |
| Operation (14%) | 80 |
| ESA project (14%) | 80 |
| Margin (12%) | 70 |
| Total | 550 |

\*1 Price for 4 to 6 balloons with 3 m diameter.

\*2: With small payload on orbiter (90 kg including instrument related to orbiter), orbiter is as simple as Venus Express, giving low price estimate

---- to be used in final---

**1.1. Past, current, and planned missions**

Past missions have revealed some qualitative differences. Soviet Union's Venera and Vega missions revealed basic atmospheric structure from the extremely hot surface to the existence of super rotation in and above the cloud layer (Schubert and Whitehead, 1969) and high acidity there (\*\*). NASA's PVO revealed many plasma features including the super rotation of ions in the ionosphere (Miller and Whitten, 1991), the latter of which is confirmed by Venus Express (Lundin et al., 2013, 2014), and the Magellan mission made a geographical map of Venus (\*\*), which raised many questions.

These basic features were farther investigated with VEX and Akatsuki. VEX investigated planetary evolution (D/H ratio and escape), cloud thermo-dynamics, and surface hot spot, whereas Akatsuki investigated the super rotation and relevant gravity waves of the cloud layer. These missions confirmed that atmospheric dynamics is essentially different from the Earth with thermal tide playing essential role with almost no role of the planetary rotation, and also raised more question on its geology.

Many of these questions will also be investigated by the coming Indian Shukurayaan mission (targeting both subsurface and cloud layer) and by three newly approved missions by ESA (EnVision) and NASA (Veritus) and Davinci targeting atmospheric chemistry). EnVision and Veritus are geology missions and will investigate the best possible geology sciences with existing technology of remote sensing and lander. Davinci will investigate the chemistry at all altitude by sampling.

In addition to them, two large-size missions are under preparation although not approved: Venera-D by Russia and Venus Cloud Explorer by NASA. They will investigate all possible atmospheric chemistry and astrobiology that can be done with single balloon. Even local dynamics in the equatorial region can be studied with these missions and Indian mission.

---- not used ---

Evolution of the Earth's atmosphere is a key science theme. Mars and Venus developed atmospheres that are markedly different from that of Earth, of which the atmosphere evolved in conjunction with the appearance of life. While the geological record gives insight in surface-atmosphere gas exchanges, atmospheric evolution can never be understood without a proper assessment of the importance of atmospheric escape. While the current neutral escape from the Earth's atmosphere is reasonably characterized to be small, the ion escape is more complicated because of the diversity of escape mechanisms, the complexity of ion escape routes, and the strong time variability of the phenomena.

Venus is the closest planet from the Earth for both distance and size. However, their environments are quite different for both over and under the surface. Almost no planetary rotation, global magnetic field, or global plate tectonics for Venus (local one might exist) with extremely high atmospheric pressure and temperature near the surface. All these lower atmospheric and solid part of the Venus are hidden by thick acid cloud. This acid environment of the cloud is difficult attribute to a selective loss of hydrogen (H and H+) compared to oxygen (O+) because both the gravity and thermospheric temperature are similar between the Earth and Venus (high surface temperature due to greenhouse effect actually require low upper atmospheric temperature). Non-thermal escape does not explain such selective loss of H+ because Venus Express showed that the ratio of H+ escape and O+ escape is 2:1.

Today's core

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