VENUS DEEP ATMOSPHERE BALLOONING:
SCIENTIFIC SIGNIFICANCE AND
TECHNOLOGICAL FEASIBILITY

Manabu D. YAMANAKA¹, Yoshihisa MATSUDA², Taroh MATSUNO³,
Nobuyuki YAJIMA⁴, Takamasa YAMAGAMI⁴ and Jun NISHIMURA⁴

¹Radio Atmospheric Science Center, Kyoto University,
Uji, Kyoto 611, Japan.
²Meteorological College, Kashiwa, Chiba 277, Japan.
³Geophysical Institute, University of Tokyo,
Bunkyo-ku, Tokyo 113, Japan.
⁴Institute of Space and Astronautical Science,
Sagamihara, Kanagawa 229, Japan.

Abstract

As a sub-program for the Venus spacecraft exploration project planning in Japan (the PLANET-B mission), ballooning from an orbiter to the deep atmosphere of Venus has been proposed. The principal objective of this sub-program is focused on elucidation of the origin of a superrotation (the four-day circulation) of the Venusian atmosphere. An instrumented, metal-skinned, water-vapor-filled and super-pressurized balloon of diameter \( \simeq 1 \text{ m} \) and weight \( \simeq 10 \text{ kg} \) is feasible for Lagrangian wind and temperature observations at the (angular) momentum maximum altitude (\( \simeq 20 \text{ km} \)).

1 Introduction

The Terrestrial Planet Exploration Working Group (WG) was organized in 1985 under the Institute of Space and Astronautical Science (ISAS). WG decided, as a candidate of the first planetary mission of Japan, to plan a spacecraft exploration project for the Venusian atmosphere and ionosphere (Ref. 1). Then the main theme was settled to elucidate the interaction between the solar wind and the Venusian atmosphere, and a sub-theme was to clarify the upward transport process from the deep atmosphere of Venus. To make this sub-theme concrete, a sub-working group for the Venusian atmosphere dynamics observations (SubWG) has been organized in January 1988.

Based on preliminary studies by WG and some projects so far made by foreign countries, SubWG has discussed the significance and feasibility of the Venus deep atmosphere ballooning from a broad viewpoint. For the present, the ballooning is a candidate of experiments by using a test spacecraft launched before the PLANET-B main mission. In this paper we report on the present status of studies toward the Venus deep atmosphere ballooning mission. The scientific significance is described in Section 2, and the technological feasibility is in Section 3. Tentative conclusions are given in Section 4.
2 Scientific Objective and Significance

2.1 Significance of planetary atmosphere dynamics studies

Planets and large satellites in the solar system are classified into the terrestrial planets and the giant planets, mainly in a viewpoint of the dimensions and interior structures. However, the atmospheres of the terrestrial planets such as Mercury, Venus, Mars and the earth are very different from each other. In general, atmospheres (including the earth's oceans) redistribute energy and angular momentum; they define the surface temperature of a planet through convections as well as radiational processes, and affect the planet rotation through the tidal effects. Varieties on the planet rotations and surface conditions are manifestations of the histories of dynamical processes of each atmospheres. Thus the dynamics of the planetary atmospheres are one of the most important problems to clarify the origin and evolution of the solar system.

For the earth's atmosphere, meteorological phenomena with time scales between the rotation and revolution periods (i.e., from one day to one year) have been studied well. However, phenomena out of this period range (climate, clouds, internal waves, etc.) have not been clarified. Most of these poorly clarified phenomena are common in the other planets or related to history of the whole solar system. In particular, the climate (or the earth's environment) problem becomes urgent recently, but we have not established an effective research strategy for such an atmosphere inexperienced by the human beings. We believe that a strategy required in the earth's climate studies must be obtained by studying the atmosphere of another planet.

The planetary atmosphere dynamics including the earth's meteorology is affected not only by external conditions such as the rotation, gravity and surface orography, but also by interior properties like the radiations and phase transitions of minor constituents. Furthermore, an important role is played by phenomena which are much larger than the molecular motions but quite smaller than the planetary-scale circulations (e.g., mesoscale waves, convections and turbulence). Therefore, to clarify a dynamical phenomenon in the atmospheres is much more complex and difficult than to measure a wind velocity in a classical category of hydrodynamics. In particular, dense and massive atmospheres of Venus and the giant planets may not be applied with the conventional framework of the earth's meteorology. Such a study may lead to an advance of the general field of fluid physics.

2.2 Problems of Venus atmosphere dynamics

The Venussian atmosphere is about 90 times as dense as the earth's one, and has a scorching bottom temperature ($\approx 470^\circ$C), as shown in Fig. 1. The composition is almost occupied ($\approx 96\%$) by carbon dioxide (CO$_2$), in which clouds of sulphuric acid (H$_2$SO$_4$) exist. The vertical structure is characterized by a thick troposphere ($\approx 65$ km) and a low homopause ($\approx 130$ km). These properties have been explained by runaway green-house effect and tidal breakdown theories (Refs. 5-7), but poor knowledge on the dynamical processes particularly in the deep atmosphere lower than 30 km prevent our understanding them completely.

There is a superrotation, called "four-day circulation", at the top of the Venus troposphere, which reaches about 60 times as fast as the solid Venus rotation. This is the reason why the Venus atmosphere does not have a severe difference between the day- and night-side hemispheres, although the solid Venus rotation is quite slow ($\approx 1/243$ of the earth). It governs smaller-scale convections and waves which may play important roles in the vertical structure of the Venussian atmosphere. Nevertheless, as will be mentioned below, the origin and detailed features of this circulation have not been elucidated. Therefore, the four-day circulation is the
biggest problem in the Venus atmosphere dynamics.

Foregoing studies on the four-day circulation are classified into the following two categories:

(a) explanations and simulations of the wind profile which takes a maximum at the top of the troposphere; and

(b) investigation on why such a great amount of angular momentum (the maximum exist at the deep atmosphere around 20 km altitude) is transferred from the solid Venus, and is sustained steadily in the atmosphere.

Many studies are of the category (a), which regard processes corresponding to (b) as a black box and use some ad hoc assumptions (Refs. 8-10). A simplified problem without time dependency has been solved, but the result leads to multiple equilibria including not only the four-day circulation but also a convective circulation between the day- and night-side hemispheres (Ref. 11). In the latter circulation the net angular momentum relative to the solid Venus becomes zero. Therefore, some unknown mechanisms working on the process (b) at the deep atmosphere are inevitably necessary to select the four-day circulation.

### 2.3 Foregoing observations

Because the sulphuric-acid clouds exist at the top of the Venusian troposphere, the discovery and earlier observations of the four-day circulation was done by cloud trackings in ultra-violet photographs (Refs. 12 and 13). In 1970's a number of US and USSR spacecrafts were entered into orbits surrounding the Venus, and wind fields above 50 km altitude were derived from temperature fields based on occultation data of radio waves transmitted from the orbiters (Ref. 14). These observations revealed that the four-day circulation might ex-
tend to all the latitudes at the top of the troposphere, whereas the meridional flow might be much weaker than the zonal superrotation. However, some observations suggested a single maximum at the equator, but others detected plural maxima in mid-latitudes. Note that these indirect observations of atmospheric motions are not always correct; the cloud motion is strongly dependent on distributions of the smaller-scale vertical flow perturbation as well as the humidity, and the temperature-derived wind is valid only under an assumption called “cyclostrophic equilibrium”.

The orbiters have dropped a number of landers, which provide vertical profiles of the Venusian superrotation. The observed wind velocities decrease almost monotonically toward the surface. On the basis of these (only 14 in total) profiles, numerical calculations suggest that there may be a multiple structure of the meridional circulations in the Venus troposphere (Refs. 15 and 16). However, they are not coincident with each other, because the foregoing observations are too scarce to determine the temporal/meridional variations and to model the transfer and accumulation mechanism of the atmospheric angular momentum.

In 1985 twin USSR spacecrafts named VEGA-1 and -2 flew by the Venus on the way to comet Halley observations, and each of them inserted a balloon into the equatorial upper tro-

![Fig. 2 Dispersion diagram of internal waves in the Venusian (solid curves with hatches) and earth’s mid-latitude (dashed curves with small dots) atmospheres. In general, there are “acoustic modes” (A) and “gravity (buoyancy) modes” (G); the latter has a cut-off frequency at the Coriolis frequency (twice of the vertical component of the rotation angular velocity). In case of the earth’s mid-latitude, the third mode of internal waves called “planetary (Rossby) mode” (P) and an external mode corresponding to cyclones (B) can exist. A disturbance detected by the VEGA mission described in Subsection 2.3 is indicated by the large dot, under an assumption of orographic wave (the frequency relative to the solid Venus is zero).](image-url)
osphere of Venus (Refs. 17-18). The balloons were tracked by a network of 20 large antennas of ten countries on earth, and their locations were determined by VLBI technique (Ref. 19). This epoch-making experiment was fairly successful, and the superrotation was proved to exist almost steadily (within about two days at least), except for a severe vertical wind disturbance observed over a mountainous region (Refs. 20-21), and a weak but steady meridional motion detected by one balloon. The disturbance may be associated with an internal gravity waves induced by the mountains (see Fig. 2), and the meridional motion may be associated with a meridional circulation. However, these hypotheses cannot be concreted any more, because the observations were limited to only two trajectories at the equatorial upper troposphere.

2.4 Objective of the present sub-program

From the discussions in Subsection 2.2, one can find that the deep atmosphere observations must hold the key to solve the four-day circulation puzzle. However, as mentioned in Subsection 2.3, the observations so far made were almost limited to higher altitudes. Now we are planning to attack a deep atmosphere observation using a balloon. Our direct and final objectives are

- to observe temporal and spatial variations of winds at the momentum maximum altitude (≈ 20 km); and

- to clarify the mechanisms of momentum transfer and accumulation which produce and maintain the four-day circulation,

respectively. Combining the results of our sub-program with those of the PLANET-B main mission, we expect to obtain a much more complete picture than before for the Venusian atmosphere from the lower troposphere to the top of the ionosphere.

Fig. 3 Configuration of the Venus deep atmosphere ballooning sub-program. See text for details.
3 Feasibility of Venus Deep Atmosphere Ballooning

3.1 Total plan

Our sub-program is planned to use an "engineering test spacecraft" which will be launched before the PLANET-B main mission. It may be launched in September 1995, if the main mission is done in March 1996. As illustrated in Fig. 3, our spacecraft consists of an orbiter and a capsule; the orbiter tracks the balloon to be launched from the capsule. At first, the spacecraft is entered into an elliptic orbit with a perigee of 180–250 km, and the capsule is separated from the orbiter near the perigee. After the capsule separation, the orbiter is reentered to a circular orbit at an altitude \( \approx 1000 \) km. The balloon is automatically launched from the capsule at \( \approx 50 \) km altitude by a timer, and it finally arrives at a floating altitude \( \approx 20 \) km. We plan a horizontal flight during \( \approx 5 \) days near the equator which corresponds to about one half of equatorial circumference, if the mean wind speed is not so far from the data available from the foregoing lander experiments. The observed quantities are

- horizontal wind by balloon tracking; and

- atmospheric pressure and temperature derived from measurements of the interior pressure and temperature of the balloon.

How to derive the wind, pressure and temperature from the directly measured data is described in the next subsection.

The instrumentations for the present sub-program are listed in Table 1. The container sustains the balloon capsule from the launch of the spacecraft at the earth through the separation from the orbiter at Venus. The tracking receiver tracks the balloon, and demodulates the signals from the balloon. The tracking principle is not so far from but more compact than that used on the ARGOS platform of NOAA satellites (Refs. 22-23). A sequence of two or three parachute (weight \( \approx 5 \) kg is included in the capsule in Table 1) is used during the capsule descending. An international collaboration may be expected to develop the flight model, because the systems used in the VEGA mission (Refs. 17-18) is considered applicable to the present sub-program except for the balloon itself (see Subsection 3.4).

<table>
<thead>
<tr>
<th>Container</th>
<th>12 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking receiver</td>
<td>2 kg</td>
</tr>
<tr>
<td>Capsule (including parachutes)</td>
<td>10 kg</td>
</tr>
<tr>
<td>Balloon (floating total weight)</td>
<td>10 kg</td>
</tr>
<tr>
<td>Gross weight</td>
<td>34 kg</td>
</tr>
</tbody>
</table>

Table 1: Payloads for the Venus deep atmosphere ballooning sub-program.

3.2 Deep atmosphere balloon

The floating altitude of a superpressure balloon is determined by the total weight \( M \) and the balloon radius \( r \); the atmospheric density \( \rho_A \) at the floating altitude is given by

\[
M = \rho_A \frac{4}{3} \pi r^3
\]  

(see Fig. 4). The interior gas is filled in order to obtain the buoyancy force and to support the
Fig. 4 Floating altitude as a function of the balloon diameter with parameterizing the total weight. The VEGA balloon and our deep atmosphere balloon are indicated by a dot and a circle, respectively.

Balloon skin resisting the outside atmospheric pressure. Using a molecular weight ratio 44/18 = 2.4 of the atmosphere (CO₂) to the interior gas (H₂O), we need the interior gas of

$$\frac{6}{2.4-1} = 4.3 \text{ kg}$$

for a payload of 6 kg. The water inside the balloon is liquid from the launch at the earth to the arrival at the Venus deep atmosphere, and then becomes gas by evaporation associated with hot temperature of the surrounding atmosphere.

When we enter the balloon of a constant volume [=(4/3)πr³] from the capsule into the Venusian atmosphere, the pressure \(p_B\) and temperature \(T_B\) of the water inside the balloon varies along the thick curve in Fig. 5. There is liquid water and saturated water vapor in a thermal equilibrium given by the Clapeyron-Clausius equation:

$$\frac{d(\ln p_B)}{d(\ln T_B)} \propto \frac{1}{T_B}.$$

(2)

Arriving at the point C, the water evaporates completely, and then the Charles’ law holds:

$$p_B \propto T_B.$$

(3)

On the other hand, the surrounding atmospheric temperature \(T_A\) and pressure \(p_A\) distribute as shown by the thinner curve in Fig. 5. Therefore, if we let the floating altitude to be just at A or at C by setting \(M\) and \(r\), this “ideal” balloon becomes a zero-pressure balloon (\(p_A = p_B\)) under a thermal equilibrium (\(T_A = T_B\)).
Fig. 5 Thermodynamic diagram of water in the balloon (thick curve) and the Venusian atmosphere (thin curve). See text for details.

However, there are always some disturbances in the actual atmosphere which may break the thermal equilibrium. In case of A, the interior temperature variation from the equilibrium induce a force for the balloon to leave from the equilibrium altitude. Hence, A is an unstable equilibrium point, so that in this case we need some auto-ballasting or -valving for keeping the floating altitude. In case of B, we can expect a stable equilibrium, but we need a very strong structure to persist a superpressure between the points A and B. If we reduce the amount of water, the superpressure state becomes weaker but a “subpressure” state appears at the floating altitude B. Thus, in any case, a sufficiently strong skin is necessary, and we are now continuing a model study in order to obtain an optimum case.

<table>
<thead>
<tr>
<th>Table 2: Specifications of the Venus deep atmosphere balloon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Skin</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Total weight</td>
</tr>
<tr>
<td>Gas</td>
</tr>
<tr>
<td>Entry location</td>
</tr>
<tr>
<td>Floating altitude</td>
</tr>
<tr>
<td>Observation span</td>
</tr>
<tr>
<td>Instruments</td>
</tr>
</tbody>
</table>
Specifications of the balloon planned in the present status are summarized in Table 2. During the horizontal flight, we are going to observe the balloon location by the Doppler modulation of radio wave from the balloon. Calculations of the atmospheric temperature and pressure are carried out by using the data of the interior temperature and pressure and the relationships of the density conservation and thermal equilibrium.

3.3 Mission coordination and international collaboration

The PLANET-B main mission also includes some observations of the Venusian atmosphere. First, radio occultation observations using the deep space antenna of ISAS in Japan are proposed to obtain the atmospheric density, temperature and pressure profiles higher than an altitude $\approx 50$ km. Secondly, ultra-violet photographs of clouds are planned to be taken from the orbiter, and they may provide information of motions at the top of the troposphere. Thirdly, a lander sub-program has been proposed, which might utilize the balloon capsule of our sub-program. These observations, as well as our balloon sub-program, have not been decided officially, but we expect a fruitful result by combining all of them. Considering our scanty knowledge for the venusian atmosphere, SubWG has concluded that a repetition of observations described in Subsection 2.3 is valuable even now. As mentioned in Subsection 2.4, the atmospheric observations are important to the ionospheric studies which are the principal objective of the PLANET-B main mission.

At the 27th COSPAR plenary meeting (July 1988, Helsinki), many foreign investigators have recognized the importance of Venusian deep atmosphere research. An informal meeting has been held during that meeting (chaired by Dr. Jacques Blamont), and some international collaborations have been tentatively discussed. Up to now, any official endorsement of such an international activity has not been made, but the PLANET-B mission is entirely recognized as a valuable chance for the Venus observation, since the planetary missions by foreign countries in 1990's are going toward Mars. It must be noted that an atmosphere has complex processes as mentioned in Subsection 2.1, and that multi-operational observations by many spacecrafts and sounders under a world-wide international collaboration are inevitably necessary. These activities are just along a recent increase of recognition of the earth's environment problems, because an organization of investigators and techniques is necessary also for attacking any urgent problems concerning the planet earth.

4 Conclusions

A plan for development of the balloon system has been discussed by SubWG. In this plan a model of the balloon will be obtained until 1994, after some experiments at the stratospheric balloon facility of ISAS in Japan. Furthermore, some theoretical studies will be in parallel carried out by using a numerical computation model of atmospheric general circulations to be developed in the University of Tokyo. These studies are surely valuable for future scientific activities of the human beings, even if our sub-program is rejected by any reasons. SubWG is waiting for participations and cooperations of many other investigators of atmospheric sciences and space technology, because they are necessary to realize the present sub-program.

Acknowledgments: We wish to thank Professor Hiroshi Oya of Tohoku University, the chairman of WG, and also Dr. K.-I. Oyama of ISAS for their guidance and encouragement. The context of this paper is based on discussions with members of SubWG. Thanks are extended to Drs. J.E. Blamont, A.P. Ingersoll, V.M. Linkin and D. Crisp for their valuable information on the planetary atmosphere.
missions through private communications, and also to an anonymous reviewer for his careful reading of the manuscript.

References