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Estimation of Flyable Regions for Planetary Airships

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Scientific observations of Venus were conducted by two balloons. Future plans now being considered by ISAS/JAXA and NASA include a Mars airplane and other planetary balloons. This study deals with the use of remotely piloted airships as platforms for planetary observation. An airship can be placed in the target planet's atmosphere. The planet's surface topography, gravitational field, magnetic field, and atmospheric layer can be observed over an extended period of time with little effort or fuel expenditure. Taking into consideration the temperature and pressure on Mars and Venus, as well as basic limitations of airships, it was determined that a planetary airship should fly just below the cloud level on Venus, whereas on Mars there was no suitable region in which to station a planetary airship.

I. Introduction

An observational platform can be located in a target planet's atmospheric layer from 50 m for a ground probe to as high as the altitude used for satellites. Data obtained from such platforms can be used to examine the general characteristics of the planet and its atmospheric layer. Furthermore, the data can be used to validate and to complement the data obtained from satellites or ground probes. So far, balloons are the only platforms that have been successfully used. For example, in 1985, as a result of cooperation between the Soviet Union and France, balloons flew over Venus (VEGA 1 and 2) [1]. These balloons had a diameter of 3.4 m and flew over one third of Venus in 46.5 h at an altitude of 53.6 km.

Planetary observations can be classified into 6 categories depending on the location of the observational platform. These 6 categories are 1) remote sensing of the target planet from another planet using telescopes; 2) remote sensing of the target planet from a spacecraft using a space telescope that is located in another planet's orbit; 3) remote sensing of the target planet from a spacecraft that is in an interplanetary orbit, such as Mariner 2 and 5; 4) remote sensing of the target planet from spacecraft [2] that are in the target planet's orbit, like Venera 15-16 and Pioneer Venus 1; 5) remote sensing or direct observation at the time of descent under the target planet's gravitational field, such as that undertaken by Venera 1-7, or by flying a probe such as VEGA 1-2; and 6) remote sensing or direct observation from a fixed point probe on the surface of the target planet, such as that performed by Venera 8-14 or the Rover Mars Pathfinder [3]. It should be noted that studying a target planet using planetary airships located in the target planet's atmosphere is now being considered by ISAS [4,5], whereas NASA [6–9] is considering the use of planetary balloons located in the target planet's atmosphere. Furthermore, the Georgia Institute of Technology is studying the use of a Mars helicopter, "GTMARS [10]", whereas the University of Maryland is considering the use of a Martian Autonomous Rotary-wing Vehicle (MARV) [11].

Observations obtained using the methods described above are usually available either for a microscopic area over a short period of time or for a macroscopic area with low resolution. In the present study, an airship platform is presented that fits into a subcategory of category (5) that include probes with "remote sensing or direct observation at the time of descent under the target planet's gravitational field or by flying a probe." An advantage of such an airship is that energy is not needed to produce the dynamic lift that would support the weight of the spacecraft. Instead, this lift results from the buoyancy of gas inside the airship. The airship is never in danger of falling, and its flight control permits a large observational area. Moreover, the speed of the spacecraft is slow enough so that the communication delay from Earth is covered.

In the present study of a planetary observational airship, we determined the flyable region based on the pressure and temperature in the atmospheres of Venus and Mars, and the required size and mass of the spacecraft.

II. Planet Observation Platforms

In this section, the flyable regions for possible observational platforms located in the target planet's atmosphere are discussed.

It is known that the lifting force affecting the aircraft is proportional to the density of atmosphere and the gravity of the target planet. Furthermore, the weight force affecting the aircraft is proportional to the gravity of the planet. Thus, the relative order of the flyable regions for different spacecrafts does not depend on the gravity of the planets. Figure 1 shows the relative order of the flyable regions for different spacecrafts.

Though it is possible for a satellite to reach the top of the atmospheric layer, it is difficult for an aircraft to do so. The observation of the planetary atmospheric layer is best carried out by aircraft. Heavier-than-air (HTA) aircraft with a propulsion system have extensive three-dimensional movement. However, the ceiling height of HTA is lower than that of balloons due to the weight of the propulsion systems. Should fossil fuels be used to maintain a velocity sufficient to generate the aerodynamic lift for the HTA aircraft, then the HTA with such a propulsion system could not maintain the same altitude after the fuel is completely consumed.

On the other hand, balloons can fly anywhere in the atmospheric layer. However, they are unable to hold a fixed position in the presence of wind; they are thus unable to perform three-dimensional motion. In fact, balloons can only be controlled in the leeward direction from the wind.

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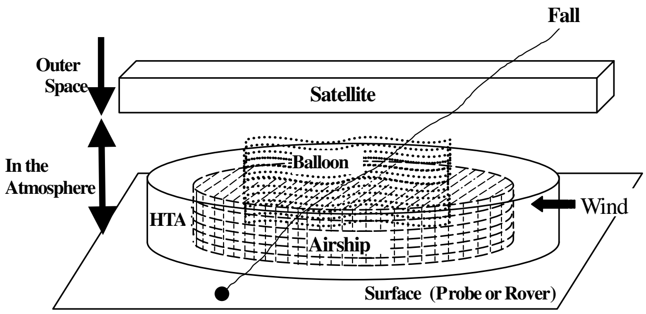

Fig. 1 Relative order of the accessible regions based on the available survey platforms.

The maximum pressure height (ceiling) of airships is not as high as that of balloons due to the weight of their propulsion systems, but this ceiling is as high as that of the HTA ceiling. Furthermore, airships can move not only vertically, but also in a plane, and can maintain a fixed position, depending on the wind speed and the airship's propulsive force. The operating time span of the airship can be extended by using solar energy to generate the propulsive force. Finally, if flight control is lost, an airship will behave like a balloon and can still observe the planetary atmosphere while floating about.

Thus, airships have the characteristics of both HTA aircraft and balloons. Therefore, airships are expected to be the most effective platform to study a planet's atmospheric layers.

III. Fundamental Limitations of an Airship

An obvious limitation for airships is the buoyancy of the gas. Other less obvious limitations include

1) The environmental temperature of the atmospheric layer that the airship may operate in varies from 218 to 398 K. This temperature range is derived from the military specifications and standards (MIL-PRF-38535F-A3.1.3.31 [MIL-M-38510J-3.1.3.31] and MIL-PRF-38534E- 3.1-ClassK) for electronic devices. In addition, electronic parts, without cooling devices, should be operated under the highest allowable temperature, that is 398 K. In the present study, in order to reduce energy consumption, it is assumed that no additional heating or cooling devices are used by the airship. Thus, the temperature range given by the above military specifications may be applied to this airship;

2) An airship can be used only in the absence of corrosive atmospheric species, such as sulfuric acid (discussed in Sec. IV). The presence of corrosive species would require the use of anticorrosive materials in the construction of the envelope. Thus, reinforcements would be needed in order for the envelope to maintain its shape;

3) The airship should operate in an atmospheric pressure greater than 10^3 N/m^2(=0.01 atm), because it is difficult to generate a sufficient lifting force for airships at pressures less than 10^3 N/m^2. At such pressures, balloons or satellites, which need a smaller lifting force, or instead require a centrifugal force instead of a lifting force, may be more appropriate for performing planetary observations;

4) The maximum overall length is assumed to be 300 m, whereas the volume of the airship's envelope is assumed to be 200,000 m^3. This size limitation for a planetary airship is based on the largest airship that can exist on Earth, an LZ-129, built by Zeppelin in 1936 with an envelope volume of 200,000 m^3, and an overall length of 245 m [12]. The performance of airships that are larger than this may not be verifiable on Earth.

IV. Planetary Environment in the Atmospheric Layers and the Flight Region

The gravitational field of a planet is not uniform. Weather changes that are caused by heat exchange in the atmosphere generate a corresponding change in the buoyancy of the airship. The planetary geography is usually not flat, which results in obstacles for the airship. Because the planetary environment is not known beforehand, it is necessary for the airship to examine the geography of the planet and send the information back to the Earth. Thus, high reliability is required for the experimental airship. In addition, the delay time for radio contact between the Earth and the planet must be taken into consideration when designing the observational system, as well as the airship's control systems. This time delay implies that real time remote control from the Earth is impossible. Instead an autonomous feed-forward control is required for the airship. The accessible flight region of the airship may be reduced depending on the structural materials used in its construction. Furthermore, the accessible flight region is limited by the temperature conditions required for the electronic devices installed on the airship. The temperature of some planets may deviate greatly from terrestrial conditions, that is, the temperature may be above 400 K or below 200 K. In addition, sulfuric acid may be present in the atmosphere, or lightning may frequently occur, which causes disturbance noise in the installed electronic devices. Finally, weather conditions, such as wind speeds in excess of 100 m/s, may limit the airship's flight region.

In the present study, airships for use on Venus, where the atmosphere is denser than on Earth, and on Mars, where the atmosphere is less dense than on Earth, are considered. Because the distance to these planets from Earth is less than that of other planets, the radio delay is shorter than that for other more distant planets, and data concerning the flight environment on these two planets is relatively easy to collect.

As can be seen from Table 1, which shows the characteristics of the planetary environments [13], the atmospheres of both Venus and Mars differ significantly from the terrestrial atmosphere. For example, on Venus, a large sulfuric acid cloud exists between the altitudes of 45 and 65 km, whereas winds at the surface typically vary from between 1 and 1.5 m/s, increasing to about 100 m/s at the top of the cloud level. Furthermore, Venus has an equatorial gravity of about 0.9 times that of Earth, and an atmospheric pressure of 92×10^5 N/m^2(=92 atm). On the other hand, Mars has a surface pressure of 10^3 N/m^2(=0.01 atm), a mean temperature of 215 K, a

Table 1 The environment of the planets

	Venus	Earth	Mars
Mean distance from Sun	1.082×10^8 [km]	1.496×10^8 [km]	2.279×10^8 [km]
Solar day	117 [days]	1 [days]	1.0287 [days]
Surface gravity	8.87 [m/s^2]	9.81 [m/s^2]	3.72 [m/s^2]
Mean atmospheric temperature (surface)	735 [K]	288 [K]	215 [K]
Mean atmospheric pressure (surface)	92×10^5 [N/m^2]	1×10^5 [N/m^2]	0.007×10^5 [N/m^2]
Composition of the terrestrial planet atmospheres	CO_2: 96.5%, N_2: 3.5%	N_2: 77%, O_2: 21%	CO_2: 95%, N_2: 2.7%, Ar: 1.6%
Mean molecular weight of atmosphere	43.4	28.96	43.5
Lapse rate of lower atmosphere	7.8 [K/km] (AGL 0 to 60 km) 8.6 [K/km] (AGL 60)	6.5 [K/km] (AGL 0 to 11 km) 0.0 [K/km] (AGL 11 to 20 km) −1.0 [K/km] (AGL 20 to 32 km) [under ISA]	2.5 [K/km] (AGL 0 to 40 km)
Wind speed	Surface: 1 to 1.5 [m/s] Cloud deck: 100 [m/s]	7 to 10 [m/s]	Max.: 90 to 100 [m/s]
Round trip of radio transport time from Earth	4.6 to 28 [min]	0 [min]	8.7 to 41.9 [min]

gravitational force of $\frac{1}{3}$ that of the Earth, and maximum wind speeds of 100 m/s.

Figure 2 shows the atmospheric environment on Venus. Based on the restrictions on temperature, pressure, and the presence of corrosive gases, there are two layers situated at altitudes of around 45 and 65 km. At altitudes less than 43 km, an airship cannot efficiently operate due to the temperature limitations of its electronic devices. However, observations in the region between 45 and 65 km and in the region below 43 km could be obtained using a tethered probe. The necessary envelope volume for the tethered probe will be estimated in the following section.

Figure 3 shows the atmospheric environment of Mars. A safe region for the airship is limited to the surface of Mars, because only at the surface is the temperature within the suitable range of 218 to 398 K and the atmospheric pressure is around 10^3 N/m^2(=0.01 atm).

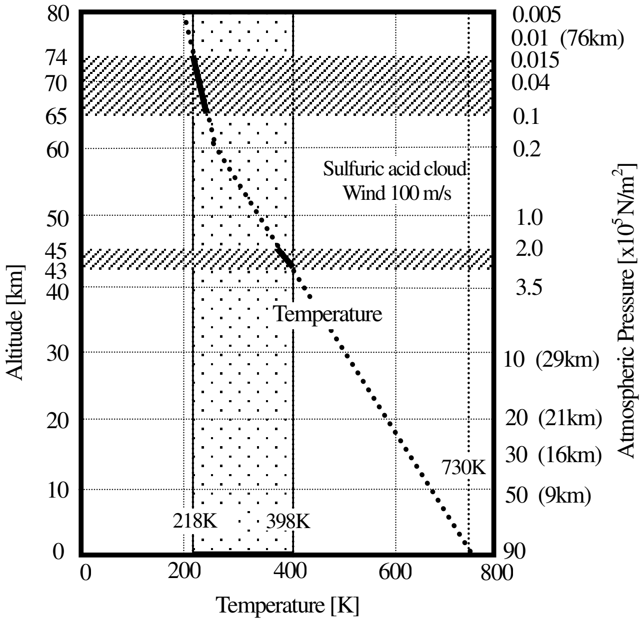

Fig. 2 The atmospheric environment of Venus together with the regions considered for the airship.

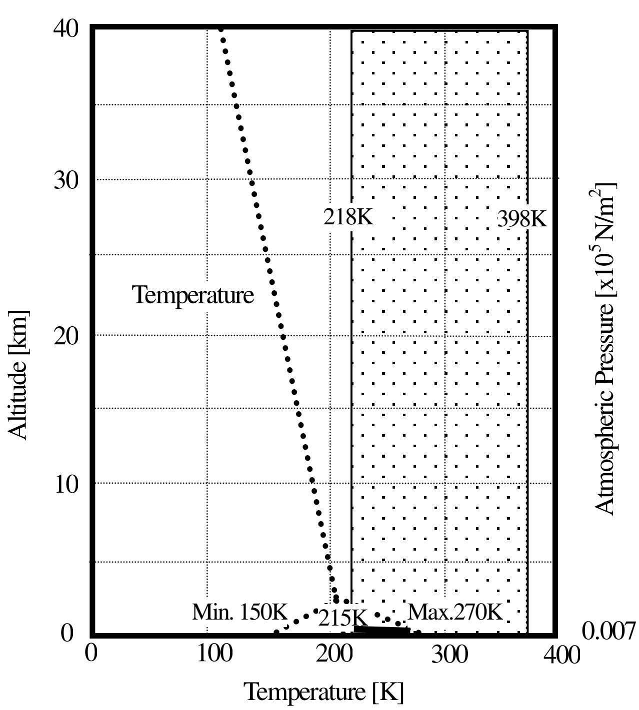

Fig. 3 The atmospheric environment of Mars together with the regions considered for the airship.

V. Required Lifting Gas and the Size of the Airship

In the present study, the specifications of an operational Earth airship [14,15] are adopted as the basic design. Figure 4 and Table 2 show the apparatus and the specifications of the baseline airship. It should be noted that in the present study, for the purpose of simplifying the analysis, the payload of the baseline airship noted in Table 2, PL, is defined as the mass of not only the usual payload but also of the structural and battery mass for the usual payload, whereas the empty operating mass of the baseline airship in Table 2, W, is defined as the mass that excludes the payload defined above. This simplified classification of the mass is hereafter used to estimate the operating empty mass of the planetary airship. The primary gaseous composition of the atmospheres of Venus and Mars is listed in Table 1. Table 3 shows the molecular weights of the vacuum and the various gases, which are available to act as the lifting gas in the planetary atmosphere. These gases are suitable because their molecular weights are less than that of the average molecular weight of the target planet's atmosphere, which is 43.5 g/mol. Table 4 shows the estimated lifting gas buoyancies per unit volume for the vacuum, helium, and nitrogen located in the region of the planets described in Sec. IV. It should be noted that in Table 4 the lifting gas buoyancies per unit volume are based on the terrestrial gravitational field in order to estimate the mass required for the airship.

In the present study, the volume of the ballonet is assumed to be 12.5% of the envelope volume. In this case, the buoyancy B is given by

$$B = 0.875(\rho_{\text{air}} - \rho_{\text{gas}})L^3 \tag{1}$$

where ρ_{air} is the density of the planetary atmosphere at a given altitude, ρ_{gas} is the density of the lifting gas contained in the envelope, and L is the characteristic length of the airship, defined as the cubic root of the airship envelope volume. The value of $\rho_{\text{air}} - \rho_{\text{gas}}$ is equal to the lifting gas buoyancies per unit volume listed in Table 4. The operating empty mass of the airship M which excludes the mass of the payload, is assumed to be

$$M = M_0\left(\frac{L}{L_0}\right)^{2.7} \tag{2}$$

Table 2 Specifications of the baseline airship

Overall length (ℓ_0)	22 m
Maximum diameter	6 m
Slenderness ratio	3.7
Envelope volume (V_0)	400 m^3
Payload (PL)	100 kg
Operating empty mass (M_0)	270 kg
Maximum flight level	1500 m
Maximum flight time	3 hours
Envelope fabric thickness	0.18 mm

Table 3 Molecular weight of various gases

Lifting gas	Molecule
Vacuum	0
Hydrogen (H_2)	2.0159
Helium (He)	4.0026
Methane (CH_4)	16.042
Ammonia (NH_3)	17.031
Hydrogen fluoride (HF)	20.006
Carbon monoxide (CO)	28.010
Nitrogen (N_2)	28.013
Nitrogen monoxide (NO)	30.006
Ethane (C_2H_2)	30.069
Oxygen (O_2)	31.999

Table 4 Lifting gas buoyancies per unit volume

Planet	Altitude [km]	Air temperature [K]	Atmospheric Pressure $\times 10^5$ [N/m^2](=atm)	Unit buoyancy [Kgf/m^3] Vacuum (atmospheric density)	Helium	Nitrogen
Venus	74 km (above clouds)	219	0.016	0.039	0.035	0.014
	65 km (above clouds)	243	0.1	0.218	0.198	0.077
	45 km (below clouds)	385	2.0	2.746	2.497	0.973
	43 km (below clouds)	397	2.5	3.328	3.027	1.179
	Surface	735	92	66.16	60.17	23.44
Earth	Surface	288	1	1.227	1.055	0.040
Mars	Surface	215	0.007	0.017	0.016	0.006

where L_0 is the characteristic length of the baseline airship. Note that the mass is not proportional to the 3rd power of the characteristic length, but to the 2.7th power, which can be explained as follows. The mass of the installed devices including the thrust systems is proportional to the 3rd power of the airship size, whereas the mass of the envelope is proportional to both the surface area and skin thickness of the envelope. The surface area is proportional to the 2nd power of the airship size. Figure 5 shows a statistical relationship between the envelope skin thickness ratio and the characteristic length ratio of existing airships, where the thickness and length of the baseline airship are used as the reference thickness and length. The thickness of the existing airships was measured by the first author of this paper, whereas the characteristic length of the airships was calculated, based on the envelope volumes listed in Jane's Yearbooks or from the maintenance manual of each airship. It can be seen in Fig. 5 that the thickness ratio is proportional to the 0.7th power of the characteristic length ratio. As the result of this statistical analysis, the exponent relating the operating empty mass with the characteristic length becomes $2.7(=2.0 + 0.7)$.

In order that an airship containing a payload mass PL be able to float in the atmosphere, the condition

$$M_0\left(\frac{L}{L_0}\right)^{2.7} + PL = 0.875(\rho_{\text{air}} - \rho_{\text{gas}})L^3 \tag{3}$$

must be satisfied. Figure 6 shows the relationship between the altitude and envelope volume that is needed for the airship with payloads varying from 1 kg to 10,000,000 kg to fly on Venus. On Mars, the relationship between the altitude and the necessary envelope volume is not shown in the present paper, because the altitude is limited to just above the surface of Mars.

In the present study, two cases are considered for the mass of the practical payload: 30 and 30 kg plus a tethered probe. In the tethered probe case, we have considered the mass of the tether as an additional 40 kg. Thus, the combined payload mass for an airship containing a tethered probe is 70 kg.

Assuming that the airship described in Sec. III uses helium, and solving Eq. (3) with respect to the characteristic length L gives the required envelope volume for an airship with either a 30 or 70 kg payload to float at a specified altitude. Table 5 shows the resulting envelope volume, the mass, and the overall length of the airship, where the mass is calculated based on its proportionality with the envelope volume, whereas the overall length is calculated based on the fact that it is proportional to the cubic root of the envelope volume. All the values are based on the values of the baseline airship, that is mass M and overall length ℓ are determined, using the calculated characteristic length L, the buoyancy per unit volume $\rho_{\text{air}} - \rho_{\text{gas}}$, and the overall length of the baseline airship ℓ_0 as follows:

$$M = 0.875(\rho_{\text{air}} - \rho_{\text{gas}})L^3 \tag{4}$$

$$\ell = \ell_0\left(\frac{L}{L_0}\right) \tag{5}$$

Airship missions with a tethered probe to locations above the clouds on Venus are considered too dangerous because the overall mass would be extremely large, which makes transportation from Earth almost impossible. On the other hand, for missions with a tethered probe to locations below the clouds on Venus, the airship would be small, and, hence, current rockets can be used to launch the airship. For missions to Mars, the envelope volume of the airship exceeds $200,000$ m^3. Thus, a more promising approach for missions to Mars would be to use HTA instead of airships.

Fig. 4 Earth observation airship.

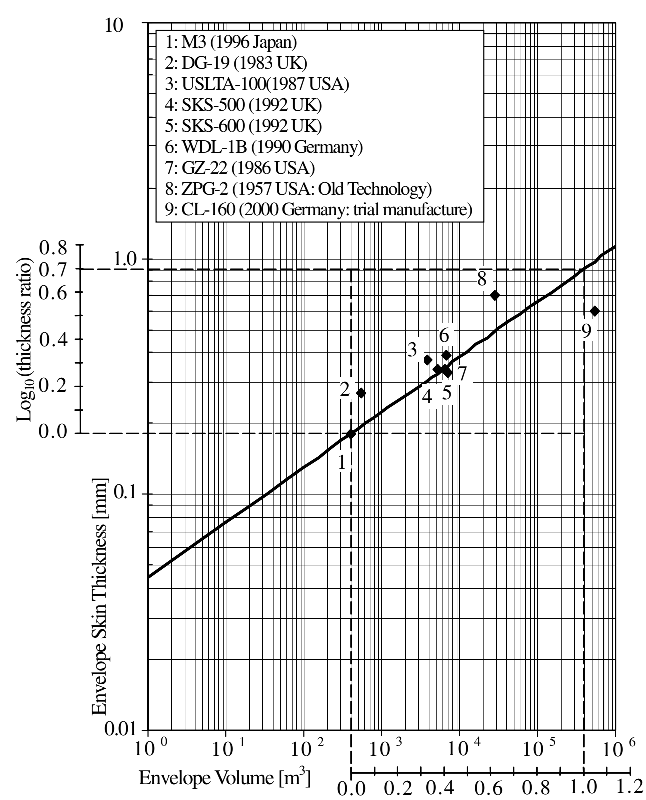

Fig. 5 Statistical relationship between the envelope skin thickness and the characteristic length.

Table 5 Estimated sizes of an airship hull using helium (bold numbers: prohibitively large)

Planet	Altitude	Envelope volume [m^3]	Overall length [m]	Gross mass [kg]
Venus (above cloud)	74 km[a]	$\mathbf{7.78 \times 10^{15}}$	**590, 000**	$\mathbf{2.46 \times 10^{14}}$
	65 km[a]	$\mathbf{4.23 \times 10^{8}}$	**2, 240**	**71, 260, 000**
	65 km[b]	$\mathbf{4.23 \times 10^{8}}$	**2, 240**	**71, 260, 000**
Venus (below cloud)	45 km[a]	23.7	8.6	51
	43 km[a]	17.4	7.7	46
	43 km[b]	39.0	10.1	103
	Surface[a]	0.6	2.5	31
Earth	Surface[a]	160	16.2	150
Mars	Surface[a]	$\mathbf{2.7 \times 10^{19}}$	**8, 960, 000**	$\mathbf{1.65 \times 10^{17}}$

[a]30 kg (normal case).
[b]70 kg (tether probe case).

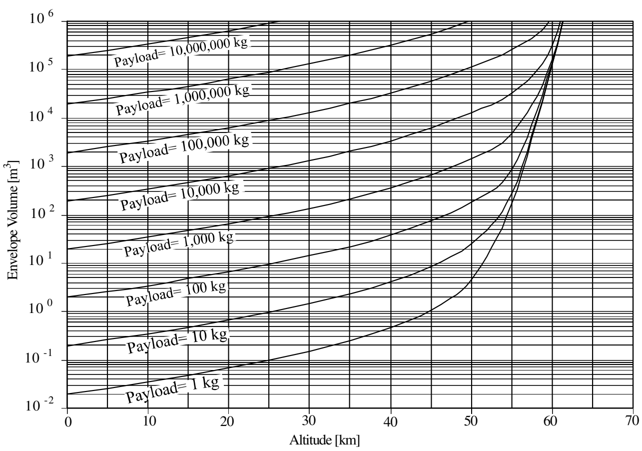

Fig. 6 Relationship between the altitude and the necessary envelope volume for an airship on Venus.

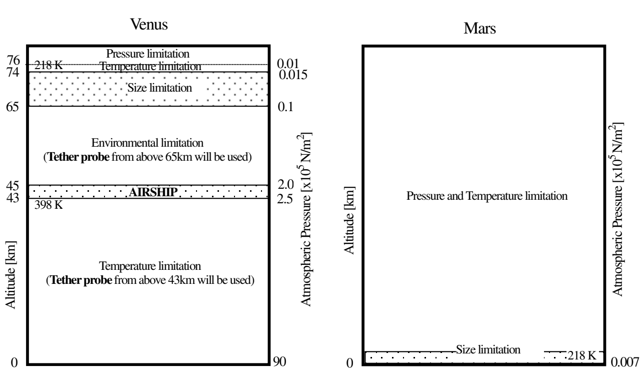

Fig. 7 Summary of possible flyable regions for the planetary airship.

Figure 7 shows a summary of the possible flight regions in the atmospheric environments on these two planets.

VI. Conclusions

Planetary airships are expected to be the most efficient platforms for observing planetary atmospheric layers because of their smaller weight compared with airplanes, and better controllability compared with balloons. The concept of a planetary airship platform has been proposed. By taking into consideration the atmospheric temperature, pressure, gravity, and presence of acid clouds on Venus and Mars, the safe flight altitudes for airships were estimated to be on Venus, two layers located at an altitude of about 43 and 65 km, and on Mars, a layer slightly above the surface. When the mean molecular weight of the atmosphere on Venus and Mars and the volume of lifting gas that is required to produce the buoyancy needed to lift the planetary airship on Venus and Mars are taken into consideration, the overall length and mass of the planetary airship can be estimated for each altitude. Based on this analysis, it was found that on Venus, the best flight altitude for an airship with a 30 kg payload was between 43 and 45 km, whereas on Mars, there are no flight altitudes with a realistic dimension for the aircraft.

Given these results based on the analysis, a study examining the feasibility and design of such an airship platform, as well as the dynamics and control of the airship, is warranted.

Acknowledgments

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