RECENT PROGRESS IN PLANETARY BALLOONS

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Abstract— In the last 15 years several balloon mission concepts has been proposed for Mars and Venus, one of them – Russian-French Mars Aerostat – was extensively developed in 1988-1995 but was terminated before completion. It became clear that a number of critical technologies yet needed to be developed prior to commit a costly space mission. In recent years significant progress has been made in two critical fields: aerial deployment and inflation of thin-film balloons, which is specifically planetary application, and in development of envelope design, which was driven primarily by Earth's stratospheric applications. The paper describes requirements, some of proposed concepts, critical elements and trade-offs in planetary balloon missions as well as current results of some of JPL balloon programs.

1. INTRODUCTION

Robotic balloons (Aerobots) may significantly change the future of *in situ* planetary exploration. Aerobots can be used to study eight solar system bodies with atmospheres; Venus, Mars and Saturn's moon Titan are the prime candidates.

Venus is the closest and the easiest planet for aero-bots. The first planetary balloons were part of the highly successful Soviet-French-U.S. VEGA mission in 1985 [1] (Figure 1).

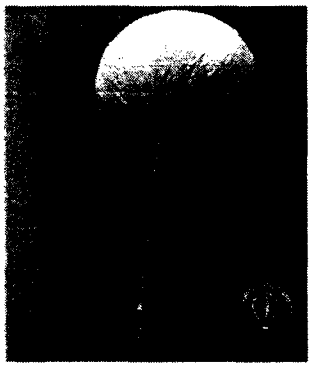

Figure 1. Vega balloon in flight test

On Venus, aerobots may serve as the scientific platforms for in *situ* atmospheric measurements and for study of atmospheric circulation. They can be used to drop imaging and deep sounding probes at sites of interest and to acquire and relay high-rate imaging data. Ascending from the surface balloon carrying a sample canister is essential for a Venus surface sample return mission. A reversible fluid balloon studied in the Venus Geoscience Aerobot concept [2] could perform vertical excursions in the atmosphere from 60-65 km down to 1-2 km altitude.

On Mars, aerobots can fill the gap in resolution/coverage between orbiters and rovers. They provide mobility two-three order of magnitude exceeding mobility of present day and future rovers traversing up to thousands kilometers per day over the areas inaccessible for other vehicles. Solar-heated balloons [3] can be used instead of parachutes to assist landing of surface packages or for 6-12 hrs science missions.

On Titan, powered aerobots (airships) can perform long duration low-altitude global flight for surface mapping, *in situ* atmospheric measurements, and deployment of surface science packages for *in situ* surface studies.

One attractive feature of aerobots that is a capability of deployment of large-size (but light-weight) antenna structures that can be used to increase resolution and sensitivity of radar science instruments and to increase communication data rate.

2. PLANETARY ENVIRONMENTS

Three candidate planets have very different environments (see Table 1). The deep atmosphere of Venus exhibits broad variations in atmospheric parameters. The high temperature and pressure in the lower atmosphere strongly limit the lifetime of surface and near-surface vehicles: without nuclear-power driven refrigerators or high-temperature electronics the lifetime would be ~ 2 to 3 hrs. High-temperature materials with good gas barrier and strength properties are needed for near-the surface Lighter-Than-Air (LTA) vehicles. On the other hand, the environment of the higher troposphere is quite mild and comparable with the troposphere of the Earth. This region is the most favorable for aerobot missions (VEGA balloons flew at 53 km at pressure 0.5 bar and temperature ~30C). The main challenge is the sulfuric acid clouds that cover 100% of Venus.

On Mars, the low density of the atmosphere in combination with large thermal variations requires light-

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weight and strong materials for long-duration aerobotic missions—a combination that is not easy to obtain. Martian troposphere is similar to the stratosphere of Earth; this similarity provides the basis for the Earth stratospheric flights to test the Martian balloon systems.

The combination of high density (four times larger than on the Earth) with low gravity (1/6 of the Earth value) and low temperature contrasts makes the Titan almost ideal for long-duration aerobot missions.

Atmospheric density dominates the balloon size: to lift a payload ~10 kg a Mars aerobot floating at 4 km altitude requires a balloon over 150 times larger (in volume) than the Venus aerobot at 60 km and over 1500 times larger than the Titan aerobot near the surface. A mass efficiency (ratio of payload mass to the total floating mass that includes mass of payload, balloon and buoyant gas) can be 75-80% for the Venus and Titan balloons and only ~20% for the Mars balloon. The most radical way to increase mass efficiency is to use lighter envelope materials.

Table 1. Planetary environments [4-6]

	Venus	Mars	Titan	Earth
Acceleration of gravity, g's	0.9	0.37	0.16	1
Main atmospheric gas	CO_2	CO_2	N_2	N_2
Surface Temperature, K	735	230	92	290
Surface Pressure, atm	92	0.0067	1.4	1.0
Surface air density, kg/m3	64	0.015	4.9	1.2
Solar flux at the upper atmosphere, W/m2	3200	700	13	1300
Solar flux near the surface, W/m2	5	700	<1?	600
Altitude of tropopause, km	~65	11		17
Pressure at tropopause, mbar	97	2.7		90
Temperature at tropopause, K	240	190	?	220
Diurnal temperature variations near the surface, $\delta T/T$, %	<0.3	30-50	<1-2	<10
Winds at the tropopause, m/s	80-100	20-30	?	20-30
Winds in lower atmosphere, m/s	1-3	5-20	<3?	5-20

3. RECENT PLANETARY BALLOON MISSION CONCEPTS

3.1. Venus

Several balloon mission concepts have been recently proposed.

Venus Multisonde Mission *[7]* Objective of the mission was to get high-resolution pictures of the Venus surface at several locations, to measure composition of the lower atmosphere and to collect meteorology data at altitude about 60 km in the equatorial zone. The mission concept is shown in Fig. 2. Main element of the mission is a super pressure balloon that would be deployed from the entry vehicle and would float at altitude 60-63 km. The balloon will encircle Venus in 5-7 days carried by 60-100 m/s zonal retrograde winds of the upper atmosphere. The balloon would carry three small imaging drop sondes (3.5 kg each) and a heavier mass-spectrometer sonde which will be released during the balloon deployment. Drop sondes would be released over geologically diverse areas of Venus (slopes of volcanoes, equatorial plains). Small parachutes would decelerate the sondes at 5 km above the surface to provide time for a high-resolution imaging. High-gain tracking antenna on

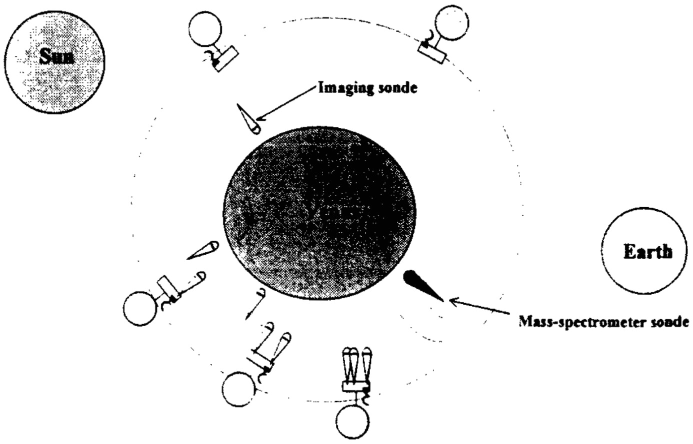

Figure 2. Venus Multisonde mission concept

the balloon relays data received form the sondes to the DSN stations. The balloon is 6-m diameter sphere with a relief valve which vents the gas after release of drop sondes. Two options of materials were proposed for the balloon. One of them is a bilaminated Mylar bladder with a kevlar or PBO scrim reinforcement and a external Teflon sheath. The other is a laminated polyester/scrim/polyethylene composite. Both – Teflon and polyethylene provide adequate protection against sulfuric acid.

Balloon for Venus Surface Sample Return mission [8,9]. Earlier ESA [8] and recent JPL study [9] of Venus Surface Sample Return (VSSR) mission call for a balloon that lifts a 450-kg Venus Ascent Vehicle (VAV) with a canister containing the collected sample to altitude 62-66 km where the VAV can be launch from without huge atmospheric drag loss. The balloon should be inflated and launched from the lander on the Venus surface and will be exposed to high temperatures for about 4 hrs during inflation, launch and ascent. The balloon is 4000 cubic meters zero-pressure cylinder. The candidate materials for the balloon were polybenzoxazole (PBO) film enclosed in a teflon shell and Teflon reinforced with PBO scrim. PBO serves as a strength element which is protected by Teflon from sulfuric acid exposure.

Venus Mesospheric Sounder [10]. Objective is *in situ* study of structure of the mesosphere of Venus at altitudes 60-80 km – an important region which was not covered previously with direct measurements. The mission uses 12-15 m diameter zero-pressure polyethylene balloon carrying a small 5-kg package for in situ temperature, pressure, heat fluxes and cloud measurements with direct-to Earth data transmission. It has close analogy to common radiosonde.

The most recent ***Balloon Precursor Mission for Venus Surface Sample Return*** concept [11] combines two previous balloon approaches and is intended to gather accurate data on Venus mesosphere, lower atmosphere and to validate key technologies for the future VSSR mission.

The mission concept is shown in Fig. 3a and 3b. The 100-150 kg entry vehicle of the precursor mission can be delivered to Venus by a spacecraft launched by a Delta 7325 class launch vehicle. One month prior to arrival the entry vehicle will be targeted to the desired location at Venus.

The entry vehicle will house two probes: Probe-1 with the mesospheric zero-pressure balloon sonde of the previous concept with inflation system and Probe-2 with the lander, gondola, lifting balloon and gas tanks.

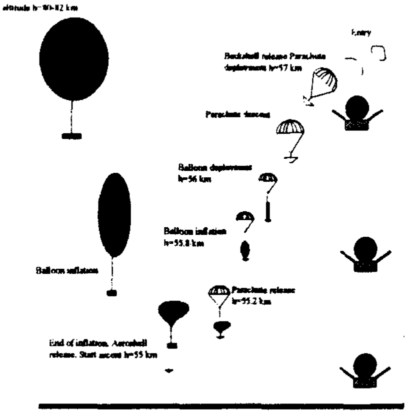

Figure 3a. Entry and Probe-1 flight profile

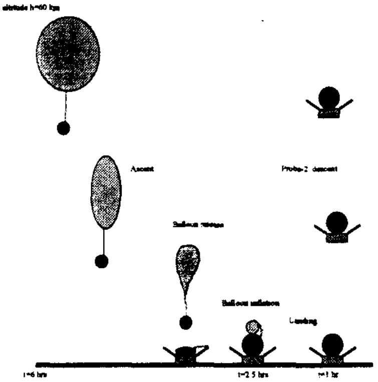

Figure 3b. Probe-2 flight profile

A small ballute will be deployed and inflated prior to insertion into the atmosphere. The ballute will be used as auxiliary decelerator in addition to the aeroshell. The recorded deceleration during the entry will help to validate the ballute performance.

At an altitude of 58 to 56 km, the back shell will be ejected and two probes will be separated: a parachute will decelerate Probe-1, whereas Probe-2 will continue a free descent. When Probe-1 reaches terminal velocity, the balloon container opens and the balloon deploys with the inflation system suspended from the bottom fitting. The inflation process lasts 30 to 60 s. Ten seconds prior to completing inflation, the parachute separates from the balloon with inflation system and gondola still suspended. Five to ten seconds after completion of inflation the inflation system will be dropped and the balloon then starts to ascend. With an expected rate of ascent of 3 to 5 m/s the balloon will reach its ceiling of 80 to 82 km in 1.5-3 hours.

Probe-2 will perform a free fall in the atmosphere and will land on the surface in 1.5 hrs; even without a parachute landing velocity would be less than 5 m/s. After 1.5 hrs of stay on the surface, the lifting balloon container will be opened and the balloon will start to inflate through an inflation pipe attached to the top fitting. In 1-2 min inflation will be completed and the balloon with the 8.5-kg gondola will be released from the lander. In 4 hrs the system will ascend to 60 km and will stay there until it will lose its free lift due to vertical atmospheric motions. During all phases data will be transmitted to the DSN over S-band direct-to-Earth (DTE) link.

The lifting balloon is a 4-m diameter natural shape zero-pressure balloon which mass is 2.1 kg based on the 60 g/m^2 Teflon coated PBO cloth material that can be used in the VSSR mission. The balloon must be filled with 1.5 kg of helium gas to provide 20% free lift, enough to get the gondola to 60 km in approximately 4 hours. Note that the balloon will be stored in a container prior to surface deployment where the balloon temperature should not exceed 300 °C as per the material specification. This container will therefore be protected by the standard insulation blanket and a Phase Change Material (PCM) arrangement to achieve this temperature requirement.

The 1.5 kg of helium gas will be stored in a carbon fiber wound composite pressure vessel with a nominal pressure of 1000 atm. Another 5-cm thick insulation blanket along with 2 kg of PCM will serve to keep the helium tank below 80°C. A simple orifice will be used to set the flow rate of helium gas into the balloon such that inflation is complete in approximately 1 minute.

Deployment, inflation and launch of the lift balloon. The lift balloon will be packed in a storage container on top of the lander. If deployed, the 4-m diameter balloon will have a length of 6.5 m. To minimize launch equipment and reduce risk the balloon will be inflated through a 1.5 m pipe attached to the top of the balloon. Due to ambient pressure and density difference, on the surface the balloon volume with all 1.5 kg helium inside will be about 100 times smaller than at 60 km altitude and diameter of the inflated part would be less than 1 m. According to Venera 9, 10 data, winds the surface do not exceed 1-1.5 m/s and the small size of balloon makes it manageable during the launch. This inflated part of the balloon (bubble) will be attached to the lander until the launch. At the launch the gondola will be disconnected from the lander's structure and the balloon will be released. A ripstitch shock absorber will be used to mitigate the shock load when the gondola will be lifted from the lander. The balloon with the gondola will reach 60 km in roughly 4 hours.

3.2. Titan

Scientific and public interest to the Saturn's moon Titan will mount after Cassini/Huegens mission. Titan is the only planet with nitrogen atmosphere with available pre-biotic components; it is a natural laboratory of origin of life and numerous discoveries are very likely. Titan will might be created specially to fly LTA vehicles. Dense atmosphere (over four times of Earth's) enable small size, highly efficient (in terms of payload mass fraction), aerodynamically optimized LTA made of robust materials. Small thermal variations enable long-duration flight with low superpressure. Cold temperature (92 K at the surface) results in virtually no gas diffusion extending flight duration; it makes also more efficient conversion from thermal to mechanical energy for propulsion. Overcast sky makes low-altitude flying vehicles the only mean high-resolution visual imaging of the surface with extended coverage.

One of the most promising concepts can be the ***Titan Airship Explorer*** mission [12]. The airship will have access to the desired location eventually anywhere on the planet; it provides a mean for global high-resolution survey of the surface in visual, infrared and radio wavelengths, maintaining almost ideal vertical orientation; it can deploy a network of surface science packages for *in situ* surface studies. Expected low winds enable exploration of the surface with more sophisticated packages that could be winched down in a station-keeping mode. As an example of point design the airship will have a shape optimized for Reynolds numbers at expected speed [13]. For a payload mass 75 kg (including propulsion) the airship will have diameter 2.1 m and length 8.4 m. Mass of hull is 10.6 kg; the airship will require 14.6 kg of helium or 7 kg of hydrogen. Twin 0.3-0.5 m diameter propellers driven with 110 W of electrical power generated by Stirling machines [x] from a nuclear power source the airship will move the airship with airspeed 4-5 m/s (350-430 km/day).

3.3. Mars

Combination of low density (0.007-0.015 kg/m3) with high diurnal temperature variations ($\Delta T/T \sim 30$-50%) makes Mars the most challenging planet for LTA vehicles. Of all balloon types only superpressure balloons could provide a mass efficient low-risk opportunity for a long duration mission with viable scientific value. Being limited with mass to be launched the balloons require materials that would combine light weight with high strength - a challenge for superpressure balloon materials and for superpressure balloon design.

The smaller balloon size decreases implementation risks since stress in the material and deployment loads increase with balloon diameter. Many of earlier approaches suffered from attempt to use relatively large balloons with heavy payloads that lead to heavy entry vehicles and prohibitively high cost and risks of the missions.

The proposed approach is to develop a first generation small-scale focused science mission that features ample performance margins in the balloons, entry, deployment and inflation system (EDI), materials, instrumentation and communication. Such a mission may provide exceptional focused science data and validate key technologies that would enable the next generation of more capable mission. Total mass of an entry vehicle should be 35-70 kg to be launched as micromission, or as an auxiliary payload on another mission, or to launch multiple balloons on a small or medium scale dedicated mission.

In long-duration flights (over hundreds of days) the balloon must handle conditions at all seasons and locations. For the first missions the requirements may not be so restrictive, so the lifetime and location should be selected to make possible a safe mission within the capabilities of current technology and the available budget. This philosophy is applied here to a typical balloon mission of the first generation [14].

The mission uses a comparatively small spherical superpressure balloon to carry the payload of 1.5-2 kg in the 2005 mission opportunity. The main objective might be a high-resolution study of magnetic field in the Southern hemisphere (35-55S, 180-210E) discovered by the Mars Global Surveyor [15].

The 2005 mission opportunity and the selected mapping area provide a favorable environment: it is near fall equinox at the Southern hemisphere after the dust storm season, when atmospheric pressure, solar radiation and temperature variations are near their average. A relatively small balloon allows use of proven materials and fabrication methods, thereby reducing the costs of the mission. The Mylar film – the material which used extensively in Earth superpressure balloons – of 8 μm thickness has sufficient strength and can be used for this mission.

The nominal float altitude should provide a sufficient clearance above the local topography given the expected balloon vertical motions. In the Southern hemisphere which is more elevated than the Northern one, a floating altitude of 6000-7000 m above reference ellipsoid (air density $11.2\ g\ m^3$) will provide sufficient clearance above the local terrain (2600-3600 m). The spherical balloon of 11.5 m diameter is required to float a 2-kg payload at 7 km altitude.

Flight profile of the balloon in presence of strong vertical winds (+/-3 m/s) is shown in Fig.4. During a daytime temperature of the balloon, heated mostly by IR radiation from the Martian surface, increases that results in increase of superpressure. A safety factor (ratio of the yield stress to actual stress) exceeds 2 that provide enough of margin for balloon performance. Even under such strong wind variations altitude variations of the balloon do not exceed +/-350 m. Superpressure variations are less than +/-20 Pa or 15% of maximum superpressure.

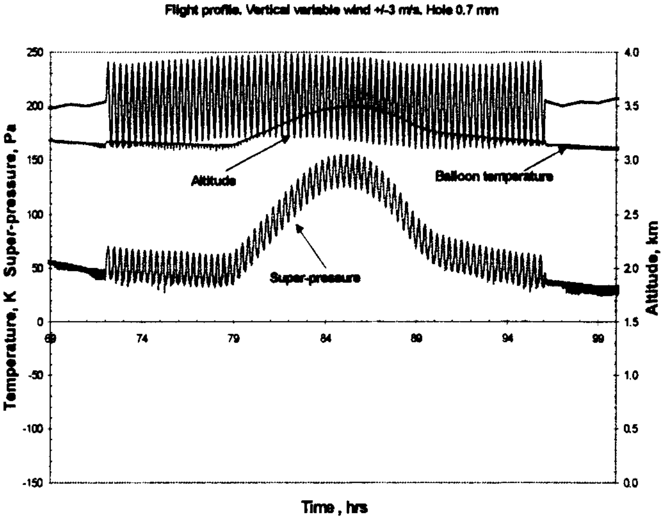

Figure 4. Balloon flight profile under variable vertical wind

4. ENTRY, DEPLOYMENT AND INFLATION (EDI)

Aerial deployment and inflation from an entry vehicle is a distinctive feature of planetary balloons that has practically no analogs on Earth. A typical EDI sequence for the Martian balloon of the Section 3.3 is shown in Fig.5.

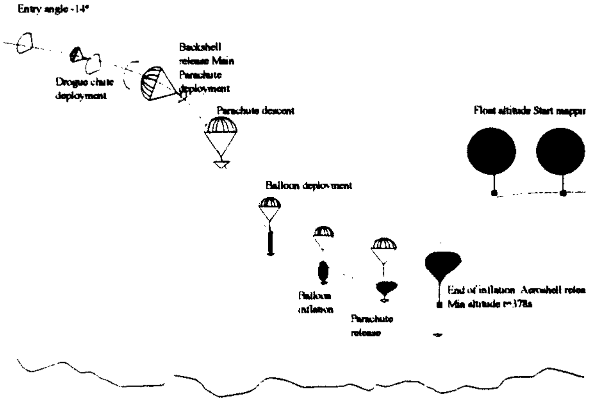

Figure 5. Typical EDI sequence for Martian balloon

Just as landing is the most critical part of lander or rover missions, deployment and inflation is the most critical part of balloon missions. In the Martian atmosphere, probe descent time is counted in minutes. This imposes requirements for rapid deployment and inflation of the balloon and leads to shock loads and aerodynamic loads on the thin film envelope. The complexity of the interaction between the light flexible membrane and non-steady aerodynamic forces makes it difficult, if not impossible, to accurately model the process from first principles.

Deployment is less risky at Venus and Titan where balloons are much smaller and more robust balloon materials can be used. The VEGA balloon built of 300 g/m^2 material (30 times heavier than 8 μm Mylar) was a good example. Deployment and inflation of balloon with much more light material (12 mm Mylar) in the environment relevant to atmospheres of Venus and Titan was demonstrated in 1998 in scope the ongoing JPL Mars Balloon Validation Program (Figure 6 [16]). Prototypes of Martian balloons are now under stratospheric flight tests.

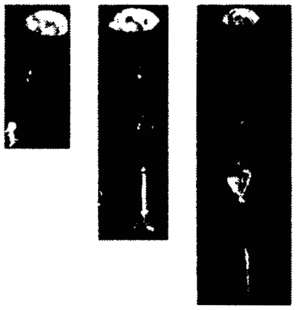

Figure 6. Tropospheric deployment and inflation of 3-m 12 mm Mylar balloon *(El Mirage Dry Lake, California, August 1998)*

5. NEXT GENERATION OF MARTIAN AEROBOTS

The next generation of Martian aerobots will employ balloons in order of magnitude larger in volume than the first generation aerobots. The inflated diameter of the envelope can reach 20-30 m and length of the gores (length of the uninflated envelope) – 30-45 m. These aerobots should fly in any season almost over any areas on Mars (except for areas around six largest volcanoes) and should withstand extremes of superpressure, controlled by extremes of the surface temperature variations. Since the stress in balloon material increases with diameter and superpressure, both these factors impose new requirements for balloon materials that could not be met with available films and traditional balloon shapes within appropriate safety margins. Larger size leads also to increase of deployment loads. Stronger materials, stress-optimized balloon designs and more benign deployment schemes are needed for the next generation of aerobots. Traditional spherical balloons may be constructed with scrim-reinforced composite materials (an example was studied in [17]) or high-strength PBO film. The "pumpkin" shape balloon which is under development in the NASA Ultra-Long Duration Balloon Program (ULDB) [18], enables significant reduction of stress in the balloon film

5. SUMMARY

Emerging planetary balloon technology makes possible Venus and Titan balloon missions in 2005 and a first small-scale focused science Martian aerobot mission to Mars in 2007. Acquired flight experience and further technology progress will enable the next generation of ultra-long duration aerobots with a composite set of instruments.

6. ACKNOWLEDGEMENTS

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