LOW-COST BALLOON MISSIONS TO MARS AND VENUS

Viktor Kerzhanovich, **James Cutts and Jeffery Hall**
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
Viktor.V.Kerzhanovich@jpl.nasa.gov, James.A.Cutts@jpl.nasa.gov, Jeffery.L.Hall@jpl.nasa.gov

ABSTRACT

The first successful flight demonstration of aerial deployment of Mars balloon prototypes in June 2002 and, earlier, of Venus balloon prototype deemed to be a turning point in the risk assessment of balloon missions. These flight tests as well as preceding development, simulations and tests brought better understanding of major influencing factors and proved feasibility of the concept. The low-cost dedicated or piggyback mission could be the first opportunity for planetary balloon missions.

1. INTRODUCTION

Though numerous planetary balloons ideas were around for a long time, the 1985 Russian-French-US Venus VEGA balloons were the only ones, which have been actually launched and successfully performed. Growing costs, limited number of planetary missions opportunities and increasingly high science competition make difficult to get a dedicated planetary balloon mission even of moderate cost. One of the reasons is that planetary balloons have still been considered as an immature and high-risk technology.

Balloon performance at float altitude can be well understood and modeled to the degree of knowledge of ambient and radiative environment of Mars and of Venus. Aerial deployment and inflation of the balloons is much less deterministic process that was studied with much less degree of certainty and for a long time it was considered as the high-risk element. VEGA balloon experience is not directly applicable because much heavier (10-20 times) fabric material was used.

Analysis, design, laboratory, wind tunnel, ground-based and ultimately flight tests is the roadmap to technology development of aerial deployment.

The most likely that at least the first balloon missions would be of a low-cost class. The key is to design a simple light-weight payload and balloon, and to decrease size and mass of the entry vehicle. It has to be carried by any major planetary mission without a burden, or to be launched by a small LV, or as an auxiliary payload on a larger LV.

2. THE LOW-COST BALLOON MISSION CONCEPTS

A number of mission concepts have been proposed in the last several years that could fit to low cost cap. Rarified Martian atmosphere limits low-cost missions to long-duration spherical or pumpkin superpressure balloons equipped with magnetometers, cameras and atmospheric instruments, and solar montgolfiere balloon serving as a lightweight decelerator for landing a surface module and, subsequently, a hot-air balloon with science payload.

Deep atmosphere of Venus provides more options for balloon missions. They may include: superpressure balloons to study atmosphere at fixed altitude levels at different latitudes, including polar regions, zero-pressure or superpressure balloons for high-resolution surface imaging in infrared, zero-pressure sounding balloons to study vertical structure of the Venus mesosphere. Both zero-pressure and superpressure balloons can drop sondes and relay data from them including high-resolution images of the surface. Eventual Venus surface sample return will require a high-temperature balloon that will bring the return rocket with sample or the sample canister to the altitude 55-65 km from where this rocket can be launched. Technology demonstration prototype of such balloon can be realized in low cost mission. Less distant *in situ* surface sample analysis would benefit from balloon that will bring the sample to the altitude where moderate environment would allow to analyze it in much more details than in harsh environment of the Venus surface.

The technology for many of these missions is either well developed or does not have major showstoppers and we hope that this decade will see the long-waited mission that will engage all balloon community.

3. MARS BALLOON CONCEPTS

It is a common statement that Mars is the most challenging planet for balloon missions. Martian environment combines rarified shallow atmosphere with great temperature variations and high topography. Pressure level of 5 mb that occurs in the Earth stratosphere at 35 km, on Mars lays at 4 km over plains in the Northern hemisphere and at 2 km over most of terrain in the Southern hemisphere. Because of low pressure even small payloads require large balloons: to carry even 2 kg payload on Mars would need balloon of 10 meters diameter.

Large daily variations of surface temperature ($\Delta T \sim 100K$ and $\Delta T/T_{min} \sim 50\%$), that are not moderated with the atmosphere, that via infrared flux determine balloon temperature, make life-time of zero-pressure balloons impractically short (one day-night transition) to justify a space mission.

These variations impose also challenging requirements on superpressure balloons that should operate at superpressure levels comparable to ambient pressure. The combination of low pressure and great thermal contrasts call for a large-size balloon made of light-weight and high-strength material – not an easy combination.

There are not too many viable low-cost mission concepts for Mars balloons. Two of them seem to be the most feasible: long-duration superpressure balloon and zero-pressure solar heated montgolfier balloon. The superpressure balloon can be used as a platform for investigations benefiting from long traverses and proximity to the surface, such as investigations of magnetic field, subsurface radar and electromagnetic studies of the inner structure, search for water with neutron spectrometer, high-resolution surface imaging and meteorology. Moving with wind at constant altitude, the superpressure balloon is an ideal wind tracer tracking of which can provide the "ground truth" for GCM simulations. The other features – almost ideal and stable vertical attitude and ability to deploy large (but light) structure - augment the balloon platform capability enabling deployment of large antenna essential for radar and electromagnetic soundings.

Zero-pressure solar-heated montgolfier balloon filled with ambient gas operates only at the day light. It primarily can be used as an atmospheric decelerator for low-speed descent and landing of the surface platforms. At the summer polar regions this balloon may serve as a platform for the science instruments.

A smaller version of the zero/overpressure balloon with a guiderope of Russian-French Mars Aerostat style could be also viable alternative for low cost missions if payload mass will be reduced to 1-3 kg and guiderope become passive. Still possibility of snagging and guiderope wear may limit lifetime and increase risk of such mission.

4. DEPLOYMENT OF MARTIAN BALLOONS

In spite of challenging and controversial requirements there are feasible options of balloons from currently available materials that can fly on Mars. Balloon behavior at steady flight can be well understood and can be simulated to design a viable approach. A spherical Mylar or pumpkin balloon made of Mylar or even of polyethylene film could be well suited for the first Mars balloon missions.

Deployment and inflation of Mars balloon is the most challenging and the less understood process that for a long time appeared to be a major showstopper in development of the Mars balloon technology. That is why the aerial deployment and inflation was the main objective of the JPL Mars Balloon Validation Program (MABVAP).

Leveraging on CNES experience with the Russian-French Mars Aerostat project we realized necessity of comprehensive tests of full-scale balloons rather than testing of sub-scaled models and similitude relationships. To make stratospheric tests affordable it was essential to use simple low mass and low-labor payloads as well as to develop a year-round capability of low-cost balloon launches.

After a number laboratory, static deployment and static inflations tests (Fig.1), and tropospheric deployment

Figure 1. *Inflation test of 10-m balloon in the Space Power Facility of NASA Glenn Research Center, July 1998*

tests, all of them being successful, in 1998-2001 we made five attempts of stratospheric flight tests, each using 10-m spherical balloon made of 12 □m Mylar film. Two of the tests failed at launch or before reaching the stratosphere. Of three stratospheric tests the balloon was successfully deployed at the first attempt but failed in the other two.

A major progress occurred since then.

After failure of balloon at stratospheric deployment in February 2001 the whole approach has been reviewed. The balloon was redesigned to improve its strength. Besides looking for different deployment schemes and devices, the main attention was paid on comprehensive tests of the balloon to better estimate its strength margins and improve models describing as static performance as, more importantly, the process of stratospheric deployment.

In 2001-2002 we performed static pull-tests and 16 deployment tests at the NASA Ames Research Center 70-m tall hangar (Fig.2) to test and characterize balloon stresses and the deployment process.

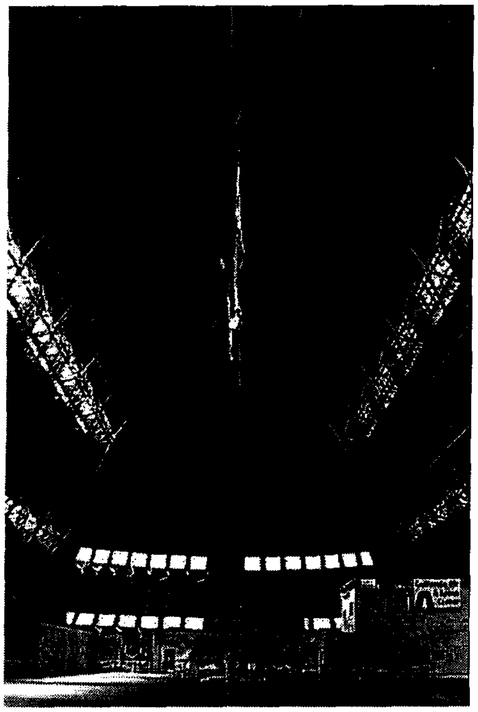

Figure 2. *Deployment test of 10-m Mylar balloon in NASA Ames Research Center hangar, April 2002*

Realizing that the relative velocity of upper and lower parts of balloon at the moment of shock is the critical factor, we simulated stratospheric deployment with system of bungees pulling balloon and payload in opposite directions – it was distinction with the earlier tests.

Fig.3 shows simulated shock propagation in the balloon at snap (White, 2003)

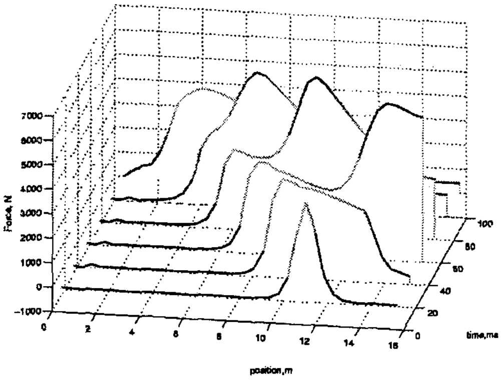

Figure 3. *Evolution of axial force in balloon during deployment snap*

It turned out that the balloon is sufficiently robust to withstand differential velocity up to 30 m/s while the expected value for stratospheric deployment was 19-22 m/s. In fact, the balloon did not fail in any of the tests when it was packed in our standard "double roll" method.

Progress in the pumpkin balloon technology (Smith et al) and preliminary tests of polyethylene in Martian temperatures (Said, 2001) allowed to include a pumpkin balloon as another Mars balloon option. The pumpkin design is better suited to the deployment since the shock will be taken by high-strength tendons and not by balloon film.

In the hangar tests of 2002 four Mylar balloons fabricated by GSSL Inc., and one 12 □m polyethylene 520 m^3 pumpkin balloon, designed by NASA GSFC and fabricated by the Raven Industries, were inspected for pinholes before and after the deployment tests. No test-induced pinholes or other damages were discovered in any of the balloons.

The other elements of the stratospheric flight train were reviewed and redesigned to include additional instrumentation, improve thermal performance and to lower risks of failures. The flight train consisted of a carrier-balloon, of a parachute with the suspended down-looking TV system and of test module that included the packed balloon, high-pressure helium inflation system, deployment system, up-looking TV system and instrumentation.

In early June 2002 two of those balloons – one spherical Mylar balloon and one pumpkin polyethylene balloon - were successfully deployed at 34 km altitude after launch from the Big Island of Hawaii.

The Mylar balloon (Fig.4) still failed 53 s after start of inflation when most of the helium was already injected.

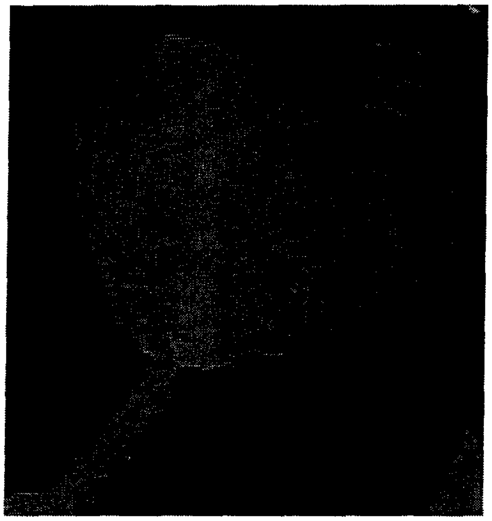

Figure 4. *10-m spherical Mylar balloon during inflation in stratosphere, June 2, 2002. The parachute is seen in the upper right part of the image taken by up-looking camera*

The pumpkin balloon withstood all inflation process visually intact. It descended to the ocean and the whole flight train was recovered. Real-time video provided complete coverage of the tests from two cameras – one (down-looking) installed on the parachute, another (up-looking) installed on the inflation module. Video coverage lasted from the launch to landing in the ocean.

Due to its shape the drag force of the pumpkin balloon took all weight of the balloon itself and of the suspended inflation module leaving the main parachute loaded only with several kilograms of TV and instrumentation units and thus simulating descent in the atmosphere with the parachute released. This situation yielded spectacular images of the descending balloon with curved Earth and Big Island of Hawaii at the background (Fig.5).

In the lower image the balloon has a distinctive spinnaker shape that did not cause any hazardous instability.

These images provide also a clue to possible cause of failure of the Mylar balloon indicating that a hardware unit above could damage the balloon. This might happen if the tether from parachute to the upper balloon fitting became slack when drag of the inflated balloon exceeded a certain value (there are many images directly showing this tether touching the pumpkin balloon).

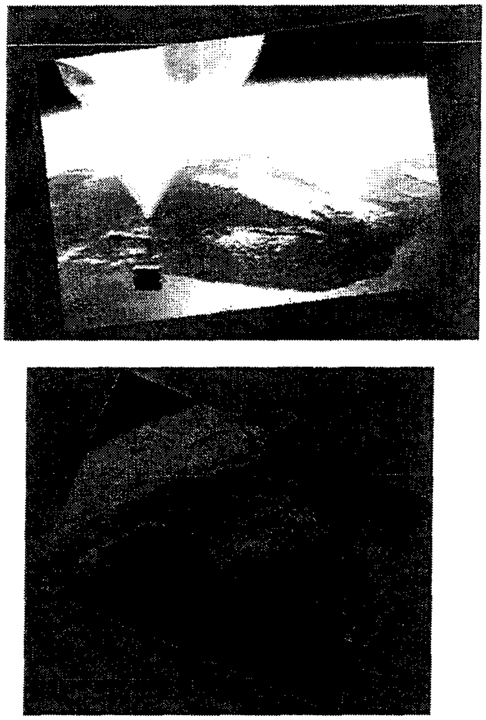

Figure 5. *Pumpkin balloon during inflation in the stratosphere. Images from the camera suspended under the parachute. June 5, 2002.*

We believe that these successful tests represent a major step in the Mars balloon technology development and demonstrated feasibility of the concept. Some modifications of the balloon and adjustment of the flight train needed to bring the Mylar balloon to the further degree of readiness.

5. VENUS

Deep atmosphere of Venus provides many options for balloons at variety of environments. Different balloon concepts can be implemented as low-cost missions. The problems for Venus balloons are high temperature at the deep atmosphere (more than +70 C at altitudes below 50 km and +460C at the surface), sulfuric acid clouds at altitudes above 49 km, as well as solar flux exceeding twice the Earth's value.

Enigmatic superrotation of the atmosphere is another key feature of Venus. Period of rotation of the atmosphere at equator at the cloud top level of 75-80 km is 4 days and it is ~20 days at 20 km (Fig. 6). Accordingly, balloon moving with wind will circumvent Venus and can serve as a "low-orbit" platform for exploration of Venus. Further we'll refine some of the concepts for Venus balloons reported earlier (Kerzhanovich and Cutts, 2001).

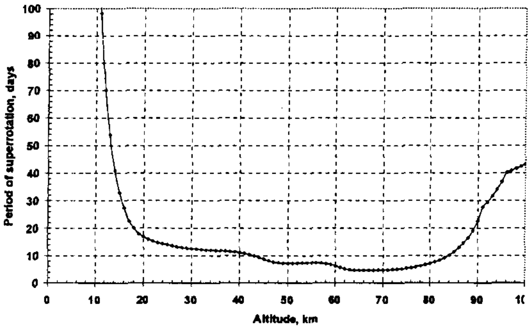

Figure 6. *Venus atmosphere superrotation period in equatorial area as function of altitude*

Balloons on Venus can be used as an independent science platform, as a radio relay for the other *in situ* vehicles, or as delivery vehicle for the probes. Much more challenging is to use balloons to lift payloads from the surface of Venus to the upper troposphere – either for detailed analysis of the surface samples (US Academy of Sciences Decadal Survey) or for launching rocket with sample for the Venus sample return mission.

Superpressure balloons are capable to make long-duration flight at a constant altitude and they would be ideal for wind tracing and for Lagrange meteorological measurements. Circumnavigating Venus they offer opportunity to survey Venus surface with variety of instruments benefiting from proximity to the surface in sensitivity and resolution - such as magnetometer, radiometer and radar. Circumnavigation also allows to pass full 117 Earth-days long Venus day in 4-10 Earth days. Constellation of balloons can be used to measure correlation in meteorological fields and even to detect Venus earthquakes.

Classic *zero-pressure balloons* can be used for study of Venus clouds region with high vertical resolution. on their ascend, float and descend phases. Though over 20 entry probes studied the atmosphere, all of them started actually direct *in situ* measurements only below 63-65 km after completion of high-speed atmospheric entry process. On the contrary, a zero-pressure balloon deployed at almost Earth environment of 54-55 km will ascend to 80 km (or 5 mb level common for Earth atmospheric soundings) in 1.5-3 hours with the first opportunity to study in details Venus upper cloud region yielding excellent science and possible discoveries [Low-cost mission]. Such measurements will provide also the first "ground truth" calibration of the numerous remote sensing from Venus orbiters. Several hours of floating at altitude of 80 km and further slow descent will augment the science return. Simultaneous delivery of the deep probe will further increase the science yielding the cross-section of the entire atmosphere,

Presently available materials would make possible balloons to float at altitudes down to 15-20 km (temperatures 300-350C) or even lower, the actual limit is imposed by avionics that presently would not normally operate at temperatures above 70-100C (47-51 km).

Detailed study of the *reversible-fluid zero-pressure balloon* capable of vertical excursions from 60 km to the surface due to condensation-evaporation of working fluid [Nock et al, 1999] showed that the concept, though eventually feasible, lays out of low-cost approach and requires significant technology development efforts presently not supported with sufficient advocacy.

Probe delivery and data relay can be another important application that use Venus superrotation. Since Venus winds at given altitude are almost constant and predominantly zonal the balloon can deliver a probe to the desired target located along the drift trajectory. Furthermore, being in proximity to the probe when it reaches the surface (normally distance between balloon and probe would be less than 200 km at that time), the balloon can receive high-rate information from probe via lower-power simple data link. The data would be stored on the balloon and transmitted to Earth using high-gain tracking antenna on the balloon during further balloon flight. Such approach simplifies greatly the probe design (and cost) and allows to transmit large volume of data including surface imaging. This Venus multisonde concept [AIAA 99] was base of VEVA Discovery proposal. The imaging probes were of 3.5 kg each and transmitted 50-100 of images of the surface.

Another low-cost option is insertion of multiple entry vehicles, each with the imaging probe and balloon. Each balloon will relay data from only one probe; the balloon could be either of superpressure or zero-pressure type. Use of a simple low gain fixed antenna will significantly reduce cost still allowing transmitting 25-30 images from each sonde.

Lifting of the payloads with balloons from the Venus surface poses major technology challenges in balloon technology (materials, seaming), in thermal protection of inflation system and balloon, and in operations – deployment, inflation and take-off.

Though such full-scale mission lay in a high cost cap some small-scale precursors could be realized in a low-moderate cost range.

Two Vega balloons were the first (and still sole) planetary balloons and served as science platforms that traversed ~ 11,000 km each in two days of flight eighteen years ago. The balloons flew at altitude 53-54 km (temperatures +25-30C). The Vega balloons were 3.5-m diameter spherical superpressure balloons made of robust sulfuric acid resistant Teflon fabric of 300 g/m^2 coated with fluoropolymer. Of 21 kg floating mass the payload was 7 kg and 14 kg were balloon with helium, thus the payload fraction was 30%. The balloons were delivered as a piggy-back inside the Vega lander entry vehicles; total mass of the balloon system including inflation and deployment subsystems was 110 kg.

With modern technology the superpressure balloons could be built of lightweight films in spherical or pumpkin design. In our Venus multisonde concept and VEVA Discovery proposal 6-m spherical balloon of 13 kg was designed to carry a payload of 44 kg. The total floating mass was 63 kg yielding payload fraction 70%.

Re-introduction of the pumpkin design allows further improve superpressure balloon performance significantly relieving film strength requirements. The balloon can be optimized for a longer endurance using materials optimized to mass and diffusion leak rate while tendons will take the pressure loads. If float altitude is not too low the polyethylene that is more than two times lighter than Teflon can be used for sulfuric acid protection further reducing balloon mass.

Aerial deployment and inflation as well as thermal environment of planetary balloons are distinctive differences with their terrestrial analogs. Fortunately, dense and deep atmosphere of Venus makes deployment and inflation easier and much less riskier. Earth surface density occurs at Venus at 53 km where the temperature is yet 50C. Completion of deployment and inflation process above this altitude does not present a major technical difficulty and can be well tested in the troposphere of Earth. Five years ago we demonstrated successful aerial deployment and

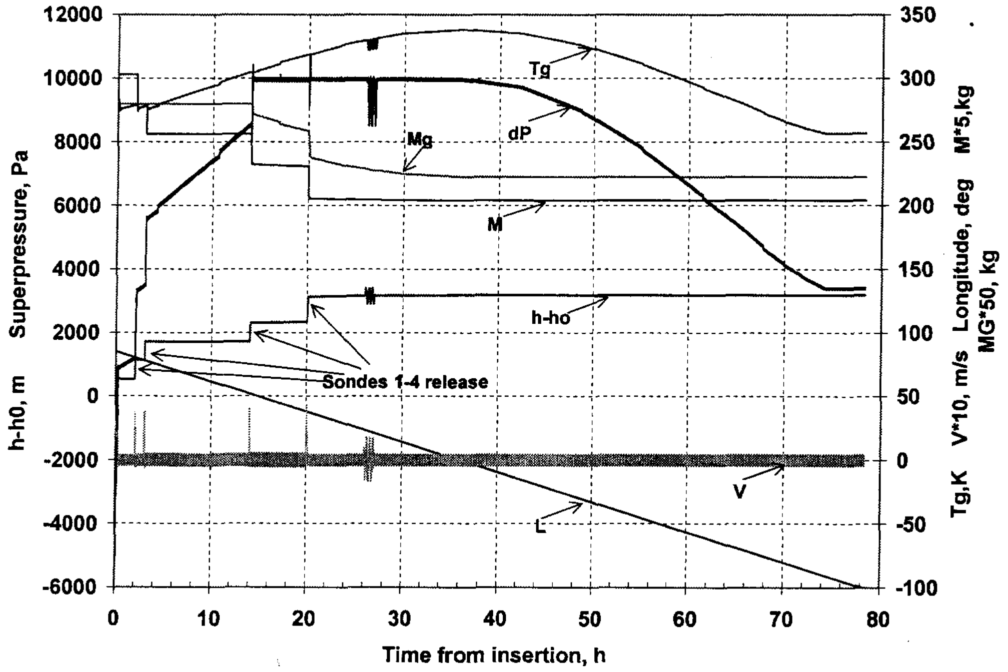

Figure 7. Flight profile of the VEVA balloon releasing four sondes

inflation of 3-m 12 mk spherical Mylar balloon. In spite of two times smaller size, the stresses in this balloon test exceeded expected deployment stresses at Venus since the material was four times thinner.

Simulated flight profile of the VEVA balloon is shown in Figure 7. At this figure Tg – balloon temperature, dP – buoyant gas superpressure, M-floating mass, Mg – mass of buoyant gas, h – altitude, h_o=58 km, V – vertical velocity of balloon, L – longitude counted clockwise from the insertion point that was located on the day side in 10° from morning terminator. Release of drop sondes manifests in several effects: decrease of floating mass and increase of lift, ascent of balloon (pulse in vertical velocity), increase of altitude and of superpressure When fourth sonde is released the superpressure exceeds a safety limit and gas is vented out. Further venting occurs due to heating of balloon by solar radiation when the balloon approaches the local noon. After that the balloon maintains the approximately constant altitude while superpressure decreases during drift to the night side. Remaining amount of gas is sufficient to maintain superpressure during the night.

In comparison with Mars, deployment and inflation of Venus balloons is much less riskier due to the facts that the balloons are smaller and more robust, deployment and inflation phase is not strictly time-limited, and descent velocities are smaller. The technology has been demonstrated in 1998 when 3-m spherical Mylar balloon was deployed and inflated after release from the helicopter.

6. LOW-COST MISSION APPROACH

Term of "low-cost" is significantly different in Earth and Deep Space programs. In NASA terms, the low cost Deep Space mission is of Discovery class mission with total cost cap of approximately $325M. The cost include all phases of the project, all labor, costs of the spacecraft design and fabrication, cost of launch vehicle, of all mission operations and data analysis.

We believe that there are several principles to make the planetary balloon a low-cost mission. First, the cruise spacecraft should be as simple as possible. The balloon payload should be light and simple. A 1-3 kg payload for Mars and 5-15 kg for Venus could be considered as "light". Significant cost savings would be for a mission without an orbiter when data from the balloon are transmitted directly to the Earth (possible for Venus) or relayed via another orbiter that is already at the planet's orbit.
There should be a compromise between science objectives and balloon capabilities that would not require a new balloon or material technology development.

The balloon and all associated systems could be quite simple and packed in a small volume. Even stratospheric module that included equivalents of all elements of the real Mars balloon and was built of the OTS components weighed only about 40 kg and could be packed in ~ 0.8 m diameter spherical segment. Preliminary design shows that the entry vehicle that will insert the balloon in the atmosphere would be 0.8-0.9 m in diameter and total mass, including balloon, of 50-70 kg – both for Mars and for Venus.

While the balloon, inflation and deployment systems are relatively cheap, the payload could be the most expensive component. By simplifying the payload the cost might be significantly brought down. In combination with the small entry vehicle the mass and cost reserve would be sufficient for a mission that would include several balloons.

In present highly-competitive and low risk tolerant environment such multiple balloon mission based on one of the concepts mentioned above would have more significant chances to win than a single balloon with more capable payload.

7. SUMMARY

Balloons enable large variety of concepts that can be implemented as low-cost dedicated or piggy-back missions to Mars and Venus. Re-introduction of the pumpkin design augmented capabilities of both Venus and Mars balloons. Recent progress in development and tests of aerial deployment brought Venus and Mars balloons to the new degree of maturity.

8. ACKNOWLEDGEMENTS

Authors are grateful for cooperation and contribution to various phases of the described work to many organizations and individuals, especially B.Dudik, H.Cooper, C.White nad M.Pauken (JPL), S.Smith, D.Fairbrother, H.Cathey (NASA WFF), A.Vargas (CNES), T.Lachenmeier and B.Moody (GSSL), M.Smith and E.Rainwater (Raven Inds.).

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

9. REFERENCES

Bachelder, A., Nock, K., Heun, M.K., Balaram, J., Hall, J.L., Jones, J., Kerzhanovich, V., McGee, D., Stofan, E., Wu, J., Yavrouian, A. *Venus Geoscience Aerobot Study (VEGAS)*. Paper AIAA 99-3856, AIAA Balloon Technology Conference, 1999

Cathey, H.M. *NASA Super-pressure Balloons – Designing to Meet the Future*. Proc. of 15th ESA Symposium on European Rocket and Balloon Programs and Related Research, pp.583-596, 2001

Jones, J.A., Rivera, J., Mahaffy, P., *Mars/GCMS/Drill Montgolfiere Micromission Payload Configuration*. Paper IAA-L-0510 presented at Fourth IAA International Conference on Low-Cost Planetary Missions, 2000

Kerzhanovich, V., Balaram, J., Campbell, B.C., Cutts, J.A., Gershman, R., Greeley, R., Hall, J.L., Nock, K.T., Winterhalter, D. *Venus Aerobot Multisonde Mission*, Paper presented at AIAA Balloon Technology Conference, 1999

Kerzhanovich, V.V. and Cutts, J.A. *Recent Progress in Planetary Balloons*, Proc. of 15th ESA Symposium on European Rocket and Balloon Programs and Related Research, pp.647-652, 2001

Kerzhanovich, V. V. , J. A. Cutts, H. W. Cooper, J. L. Hall, B. A. McDonald, M. T. Pauken, C. V. White, A. H. Yavrouian, A. Castano, H. M. Cathey, D. A. Fairbrother, I. S. Smith, C. M. Shreves, T. Lachenmeier, E. Rainwater and M. Smith, *Breakthrough in Mars Balloon Technology*, Paper PSB1-0076-02 presented at 2002 COSPAR Meeting, 2002

Said, M. Private communication, 2001

Vargas,A., J. Evrard, P. Maurois. *Mars 96 Aerostat. – An Overview of Technology Developments and Testing*. Paper presented at AIAA International Balloon Technology Conference, San-Francisco, CA, 1997

White, C.V. and S. Day, *Analysis and Experimentation for the Aerial Deployment of Planetary Balloons*, Paper presented at the *2003 IEEE Aerospace Conference*, Big Sky MT, March 9 –14, 2003