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Article1: Montgolfiere balloon aerobots for planetary atmospheres
Author1: Jones, JA; Heun, MK
Source1: AIAA, International Balloon Technology Conference
Date: June 3-5, 1997
Publisher: United States
Place: San Francisco, CA
Notes: AIAA Paper 97-1445 (A97-31330)

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AIAA

A97-31330

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AIAA 97-1445

Montgolfiere Balloon Aerobots for Planetary Atmospheres

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12th Lighter-Than-Air Systems Technology Conference
AIAA International Balloon Technology Conference
14th Aerodynamic Decelerator Systems Technology Conference and Seminar
June 3-5, 1997 / San Francisco, CA

A97-31330

MONTGOLFIERE BALLOON AEROBOTS FOR PLANETARY ATMOSPHERES

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ABSTRACT

Solar Infrared Montgolfiere Aerobots (SIRMAs) use a combination of lower planetary infrared heating during the night and solar heating during the day. A detailed study performed on SIRMA use at Jupiter shows that about 112 kg of total floating mass is required to support a ten-kg payload. The balloon floats at about 0.1 bar during the day and descends to about 0.2 bar at night, using isentropic compression heating to help slow the nightly descent rates. The total delivered mass is about ten times lighter than for comparable pure hydrogen balloon systems at Jupiter. A similar SIRMA for Saturn would weigh about 220 kg and may also be viable. SIRMAs for Uranus and Neptune, however, may be less mass-competitive than pure hydrogen balloon systems, due to the planets' greater distances from the Sun and their higher atmospheric molecular weights. Preliminary analysis shows that SIRMAs for Venus may be quite viable and might weigh as little as 20 kg for a 25-kg payload. Active control of SIRMAs for short-duration landings on Venus may be possible, although more analysis and testing is required to prove viability.

INTRODUCTION

The exploration of the solar system has proceeded in several phases, beginning with flyby missions, proceeding to orbiters, then to probes and landers, and finally to mobile vehicles that operate on the surface and in the atmosphere. For the most accessible planetary bodies, Venus and Mars, we are now entering the phase of mobile exploration of the surface and atmosphere. This paper is concerned with the use of AEROnautical roBOTS (aerobots) that autonomously conduct atmospheric and planetary exploration of the outer planets and Venus.

The Jet Propulsion Laboratory (JPL) is involved in planning and developing technology for the use of aerobots for planetary exploration. These aerobots employ lighter-than-air balloon technologies to obtain atmospheric buoyancy and provide a platform from which planetary science can be conducted. Telerobotic and autonomy technologies provide motion control in three dimensions, using winds to reach specific atmospheric and surface science targets.

The original motivation for developing a new class of robotically controlled balloons, or aerobots, was to advance the exploration of Venus[1]. In the late 1970s and early 1980s, G. M. Moskalanko of Russia did significant research into various types of controllable balloon systems for exploring the atmosphere of Venus.[2,3] One of the concepts he explored was the use of an ammonia/water balloon system that would have both the ammonia and water evaporate at Venus' hot surface, thus filling a balloon. At higher altitudes, the water would preferably condense out, thus deflating the balloon and allowing re-descent to the surface. A balloon filled with water at equilibrium would be 100 percent vapor below 42 km and 100 percent liquid above a 42-km altitude. In fact, since water is buoyant in the Venusian CO_2 atmosphere, the balloon would tend to stabilize at the 42-km altitude point. In 1981, Moskalanko proposed trapping the condensed water in a pressure vessel, thus allowing the balloon system to land for brief periods on the surface of Venus.[3] Opening a valve would allow the fluid to boil, thus refilling the balloon and allowing re-ascent.[4]

In the 1990s, work by Nishimura et al.[5] of Japan also discussed using two-phase water balloons in the Venus atmosphere. In these studies, a model experiment was performed that measured the phase transition as well as the heat transfer characteristics of a water balloon in a Venus-like atmospheric test bed.

Recently, Jack Jones of JPL[6] proposed modifications of these concepts that could enable aerobots to perform multiple controlled landings on both Venus (using water phase change) and Titan (using argon phase change). A series of highly successful flights in the Earth's atmosphere has, in fact, been conducted for a 1993–97 JPL internal research study known as the Altitude Control Experiment, or ALICE[7] (using Refrigerant 114 as the phase change fluid). Titan is not conducive to using SIRMA balloons because of the small amount of sunlight that penetrates its high stratospheric clouds.

In order for phase-change fluid systems to attain altitude control for balloons, it is necessary for them to fly in planetary tropospheres. Since Mars has no effective troposphere and is not conducive to SIRMA balloons because of a nighttime surface temperature colder than the atmosphere, an alternate balloon concept, known as superpressure balloons, has been considered.[8]

CONCEPTS USING SOLAR INFRARED MONTGOLFIERE AEROBOTS

Background

Recent studies at JPL have shown that the phase-change fluid aerobot concept and the superpressure balloon concept are far less practical for the outer gas planets than they are for Venus or Titan. The reason for this is that the outer gas planets are at least 80 percent hydrogen; the remaining atmosphere is primarily helium. In order to "float" a 10-kg payload in the Jovian atmosphere, a total mass of approximately 1,000 kg is needed for the hydrogen, balloons, tankage, phase-change fluids, and entry vehicle mass.

These same JPL studies have shown that a very promising lightweight controllable balloon system using lower planetary radiation heating appears quite feasible for some of the outer gas planets, as well as for Venus.[9] The technology is based on a modification of a design that was demonstrated by a series of 30 infrared Montgolfiere balloons flown by the French space agency CNES in the Earth's stratosphere in the 1980s.[10] The balloons' upper surfaces were aluminized to minimize radiant heat loss to space, while the balloon's inside upper surface was blackened to absorb infrared radiation heat from the lower, warmer Earth. The resulting heating of the balloon's internal air allowed missions with 50-kg payloads that lasted up to 60 days and encircled the globe. The French used the name "Montgolfiere" for their hot air balloons, since it was the Montgolfier brothers who flew the world's first hot air balloons (heated by burning wood) in France during the eighteenth century.

A sketch of the present French infrared Montgolfiere balloon system is shown in Fig. 1. The lower part of the balloon is clear mylar or polyethylene, which allows the Earth's IR radiation to pass through and be trapped by the blackened interior of the balloon's upper portion. The trapped air is thus warmed significantly above the Earth's cold stratosphere temperature. Typical altitudes attained (represented by reduced pressure) are shown in Fig. 2 as a function of time of day (lowest at night) and cloud cover (higher albedo).

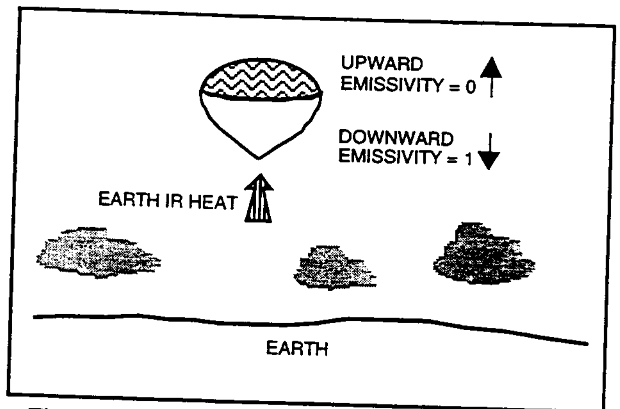

Fig. 1. Principle of Infrared Montgolfiere Balloon

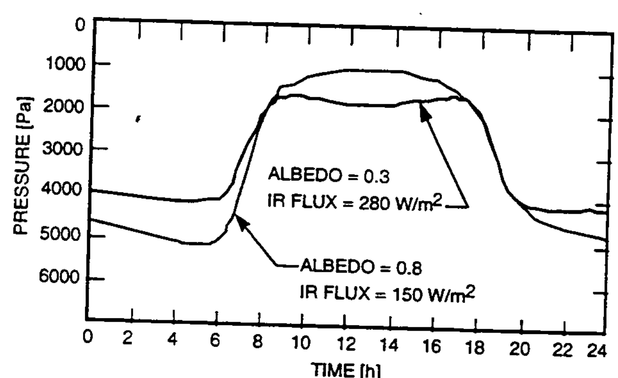

Fig. 2. Typical altitudes attained (represented by reduced pressure)

The Montgolfiere concept for other planets could also use the internally radiated planetary IR flux to heat ambient atmosphere that was collected on initial descent. As in the French IR balloons on Earth, the radiant up-welling of heat would balance the natural convection cooling from the balloon at night, while additional solar heating during the day would provide more buoyancy.

The application of Solar Infrared Montgolfiere Aerobot (SIRMA) technology to flying balloons in the Jovian atmospheres is the subject of an ongoing JPL study, and some preliminary analytical results are reported herein, while experimental work is just now being initiated.

Analysis for Jupiter

The concept proposed in this paper is a modification of the French infrared Montgolfiere design. The French Montgolfiere design limits the solar input to the balloon with an aluminized mylar upper surface. At Jupiter, an IR-only balloon is massive. The curve labeled "Without Sun" in Fig. 3 shows the floating hardware mass of a Jupiter balloon relying only on lower planetary IR heating as a function of the thickness of the balloon film. Even for aggressively thin balloon skins of about 6 μm (0.25 mil) the IR-only balloon is unacceptably massive. The curve labeled "With Sun" in Fig. 3 shows the effect of solar energy input on hardware mass. For a given balloon-skin thickness, reasonable floating masses are attainable with a solar absorbing balloon skin but impractical without solar energy input. Figure 3 demonstrates the importance of both solar input and film thickness in balloon design. Clearly, thin, solar absorbing films are required for balloon flight at Jupiter.

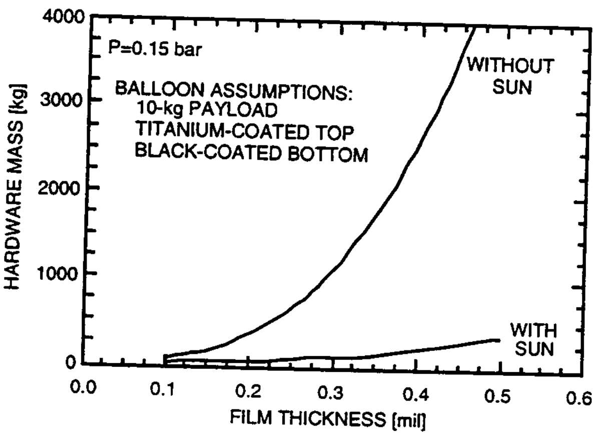

Fig. 3. Importance of film thickness

The Jupiter aerobot concept discussed here has a balloon with a titanium-coated upper surface and black bottom. The titanium upper surface provides strong solar absorptivity but limits infrared radiation to space. The lower black surface absorbs the lower planetary IR radiation.

Figure 4 shows a sample flight profile for a SIRMA flight at Jupiter using a 55-m-diameter balloon with a film that is 4.5-μm (0.1875-mil) thick. A typical Jupiter aerobot may be slightly larger and use a thicker film than the balloon shown in Fig. 4. A typical balloon may have a 60-m diameter with 6-mm (0.25-mil) film and a total floating mass of about 112 kg. During the 5-hour day, the aerobot rises due to solar energy input. At night the balloon is aided by a combination of lower planetary radiant heating and isentropic compression of the balloon's internal gas as the balloon descends from a daytime altitude of 0.1 bar to a nighttime altitude of about 0.2 bar.

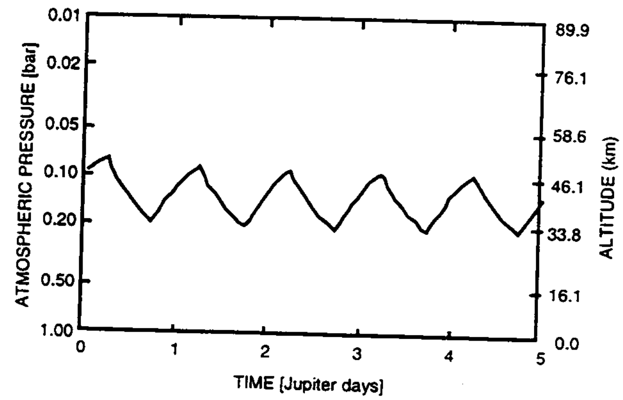

Fig. 4. SIRMA flight profile

The sawtooth pattern of the altitude profile shows that the balloon is never in equilibrium with its surroundings. The balloon constantly responds to the absence or presence of the Sun. There is a "point of no return" below which the balloon will not rise with the Sun. This occurs because the thick atmosphere limits solar radiation deeper in the atmosphere. The balloon must be large enough to capture enough solar energy to rise high enough during the day to avoid a catastrophic, low-altitude, nighttime descent.

Data from the Jupiter cloud levels (below 0.3 bar) could be obtained by means of very long tethers (Fig. 5). By using a second and third gondola, spaced 50 km apart, diurnal data could be obtained for almost all atmospheric pressure levels between 0.1 bar and 7.4 bars. A thin, strong fiber made of polybenzoxazole (PBO) could be used as a tether, with a tensile strength of over 5500 MPa (820 ksi). Since very little vertical wind sheer is anticipated, based on Galileo probe data[11], the vertical height of the gondolas may be additionally controllable by using variable lifting wings on the lowest gondola.

Alternatively, it may be possible to drop lightweight, deep atmosphere sondes from the balloon as it passes over areas of scientific interest.

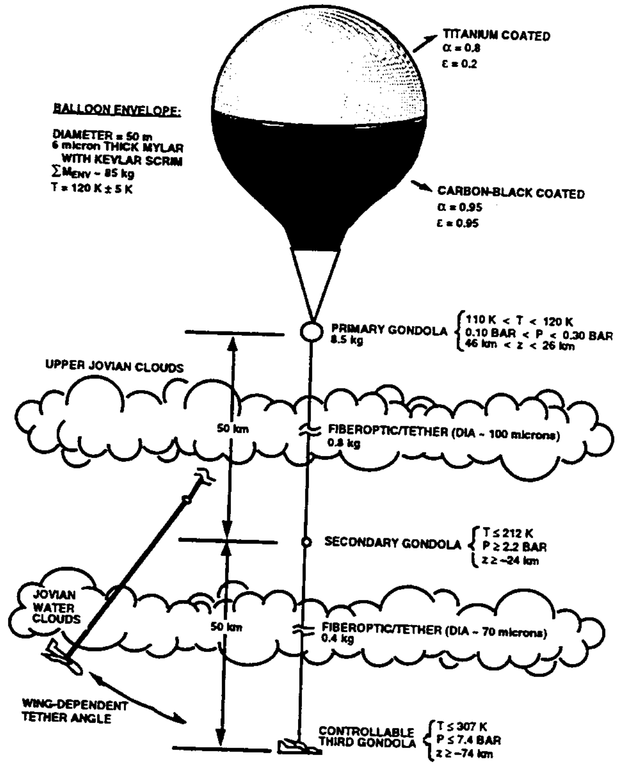

Fig. 5. Solar Montgolfiere aerobot with deployed tethers at Jupiter

Testing for Jupiter Ballons

A deployment testing program is currently in progress at JPL wherein hot-air-shaped balloons 1 m, 3 m, and 5 m in diameter are to be dropped from varying altitudes to test balloon filling/ deployment mechanisms. Each balloon size will be tested both with and without a lightweight, spring-loaded mouth-opening mechanism. At this point in the testing program, all 1-m-diameter balloons that have been dropped from a 33-m altitude have shown a 100% success rate of filling, as shown in the photograph of Fig. 6, if the spring-loaded mouth opening device is used. Without the device, none of the balloons have filled prior to hitting the ground when dropped from 33 meters.

Analysis for Saturn, Uranus, and Neptune

For comparison, balloon systems similar to the Jovian design have now been sized to float at the 0.1-bar level on Saturn, Uranus, and Neptune. As shown in Table 1, the balloon sizes and masses increase dramatically as the distance from the Sun increases. The total system weight increases to 220 kg for Saturn and 278 kg for Uranus. By the time

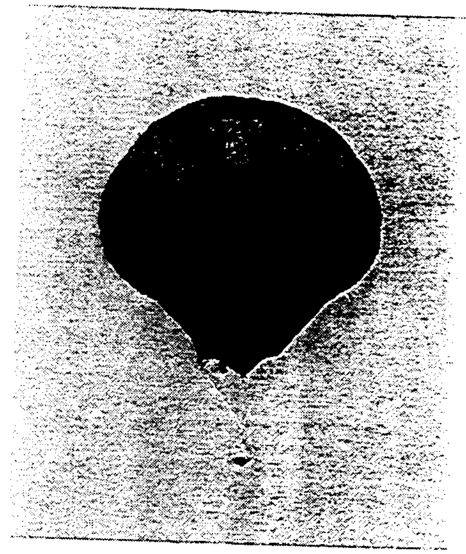

Fig. 6. 1-meter-diameter balloon

Neptune's 30-AU distance from the Sun is reached, only 0.1 percent of Earth's sunlight is available, and the balloon system mass increases to a very large 824.4 kg. Because of the increased molecular weight of the Uranus and Neptune atmospheres, balloons filled with pure hydrogen may be a preferred option, possibly with phase-change variable buoyancy, as previously indicated in Reference 8. A potential technology breakthrough regarding low-mass storage of hydrogen on carbon nano-fibers has recently been reported[12]. If this technology is valid, it could possibly make phase-change hydrogen balloons a more viable choice, especially for Uranus and Neptune.

One alternative for Saturn, Uranus, and Neptune is to use SIRMA balloons in the summer polar regions, where they would have very-long-duration sunlight.[13] This would reduce the mass of balloons for these planets by about a factor of about two.

SIRMA Balloon Concepts for Venus

Calculations performed at JPL have recently shown that for a 25-kg gondola, approximately 70 kg of additional system mass is needed for a phase-change balloon system capable of repeated brief landings on Venus.[14] Similar calculations performed for SIRMA balloons indicate that a SIRMA balloon as light as 20 kg might offer buoyancy altitude control in Venus' atmosphere. A Venus model atmosphere calculated by JPL's David Crisp[15] has been assumed in all calculations. The balloon would be fabricated of 6-micron PBO and would be about

Table 1. Outer planet SIRMA balloon sizing

Planet	Solar AU	System wt., kg	Diameter, m	Atmospheric molecular wt.	Axis Inclination
Jupiter	5.20	112.2	60.1	2.25	3°
Saturn	9.54	219.7	86.1	2.10	27°
Uranus	19.18	278.1	97.4	2.64	82°
Neptune	30.06	842.4	171.6	2.62	29°

Assumptions: Daytime float altitude = 0.1 bar
Balloon envelope = 6-micron polymer composite with 50% weight margin
Science payload = 10 kg

22 meters in diameter. It would fly in the upper clouds at night using lower planetary infrared heating. One may be able to descend briefly to the surface during the day by venting most of the balloon's hot air. Finally, the balloon could ascend back up to the upper clouds by using a combination of solar heat and planetary infrared heat to produce buoyancy in a partially inflated balloon.

One reason why SIRMAs work so well at Venus, as compared with the outer planets, is that the solar intensity remains very strong even at the surface (see Table 2). At noon at the equator the surface solar intensity is about 4.6 percent of the total incident solar intensity at Venus. Furthermore, far more radiant lower planetary thermal energy is available on Venus than on the outer gas planets, and the molecular weight of Venus' CO_2 atmosphere is much higher than that of the gas giants' atmospheres. The trapping of solar and infrared heat by the giant gas planets is due primarily to the hydrogen pressure effect,[11] which does not exist on Venus.

One major advantage of this type of hot air balloon is that pinholes and punctures may not seriously affect performance, since the balloon is filled with ambient gas only. Other advantages are the exclusion of separate buoyancy fluids and a potentially lightweight overall system.

Care must be taken to ensure a properly selected solar absorptivity coating and/or capability of greatly reducing the balloon's volume of hot gas. One disadvantage is landing only on the daylight side of Venus, although descents to within a few kms of the surface may be feasible on the night side. For very lightweight Venus aerobot systems that have a higher survivability despite leakage, however, this type of hot air balloon design may have distinct advantages.

SUMMARY AND CONCLUSIONS

Preliminary analysis shows that the combined use of solar heating with planetary infrared heating, accomplished with SIRMA balloons, appears to have distinct mass advantages over phase-change buoyancy-control systems for operation at Venus, Jupiter, and Saturn. The mass advantage of SIRMA systems versus pure hydrogen balloons and/or phase-change balloons decreases dramatically with increased distance from the Sun and with increases in planetary atmospheric molecular weight. Thus, pure hydrogen balloons, with or without phase-change buoyancy control, may be the preferred candidates at Uranus and Neptune. SIRMA balloons appear quite viable for Jupiter and Saturn, however, and would float between about 0.1 bar during the day to about 0.2 bar at night.

Very lightweight SIRMA balloons could potentially float at varying levels in the atmosphere of Venus. Furthermore, it may be possible to provide short-duration landings on the surface of Venus, although more analysis and testing is required before viability is proven. These SIRMA hot-air balloons may have a distinct advantage over phase-change balloons because of the potential for reduced mass and the lack of problems caused by the diffusion of gasses into and out of the balloon. Furthermore, pin-hole leaks in phase change balloons could cause catastrophic damage, although they would have virtually no effect for SIRMA balloons.

Deployment systems will also need to be tested to confirm validity of balloon envelope materials and thicknesses. All analyses are preliminary, and more detailed studies are presently in progress.

Table 2. Venus Atmospheric Thermal Model[15]

Pressure, bar	Temperature, K	Altitude, km	Down Solar Flux, W/m²	Up Solar Flux, W/m²	Down Thermal Flux, W/m²	Up Thermal Flux, W/m²
0.11	244.0	64.5	2623.9	2099.9	123.1	230.3
0.44	291.0	56.4	1686.7	1394.3	356.5	435.2
1.71	379.0	46.3	933.2	705.0	1155.0	1216.9
3.42	416.0	40.3	891.6	675.3	1672.0	1737.3
11.35	512.0	28.2	768.0	584.1	3864.2	3925.4
26.20	595.0	18.0	606.5	453.9	7077.2	7125.5
47.30	653.0	10.0	431.0	301.4	10,282.2	10,327.6
71.20	700.0	4.0	264.7	148.5	13,587.8	13,628.0
92.10	730.0	0.0	129.2	18.8	16,076.1	16,092.6

Assumption: Solar Zenith Angle = 0 deg.

ACKNOWLEDGMENT

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

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REFERENCES

1. Cutts, J. A., et al., "Aerovehicles for Planetary Exploration," paper presented at IEEE International Conference on Robotics and Automation, Tokyo, Japan, May 1995.
2. Moskalanko, G. M., "Mekhanika Poleta v Atmosfere Venery," Mashinosteroenie Publishers, Moscow, 1978.
3. Moskalanko, G. M., "Two Component Working Material for a Floating Probe in the Atmosphere of Venus," Proceedings, High-Temperature Electronics and Instrumentation Conference, Dec. 1981.
4. Blamont, J., "Balloons on Other Planets," Adv. Space Res., Vol. 1, 1981, pp. 63–69.
5. Nishimura, J., Hinada, M., Yajima, N., and Fujii, M., "Venus Balloons at Low Altitude," AIAA International Balloon Technology Conference, Paper AIAA-91-3654-CP, 1991.
6. Jones, J. A., "Balloon Altitude and Temperature Control," JPL Notice of New Technology, NPO #19223 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 13, 1993.
7. Nock, K., et al., "Altitude Control Experiments Results," AIAA Lighter-than-Air Conference, Clearwater, Florida, May 1995.
8. Nock, K., et al., "Overview of a Mars 2001 Aerobot/Balloon System," AIAA Paper No. 97-1447, Balloon Technology Conference, San Francisco, California, June, 1997.
9. Jones, J. A., "Phase-Change Balloons for Solar System Planets, Titan, and Europa," JPL Interoffice Memorandum 3546/280/TETCTD/JJ/93 (internal document), Jet Propulsion Laboratory, Pasadena, California, Aug. 27, 1993.
10. Malatere, P., "Long-Duration Balloon Flights in the Middle Stratosphere," Adv. Space Res., Vol. 13, No. 2, pp. (2)107–(2)114, 1993.
11. Orton, G., JPL private communication (internal document), Jet Propulsion Laboratory, Pasadena, California, 1996.
12. Hill, S., "Green Cars Go Further with Graphite," Planet Science: This Week, January 8, 1997.
13. Nock, K., JPL private communication, Jet Propulsion Laboratory, Pasadena, California, March 1997.
14. Heun, M. K., and Jones, J. A., "Gondola Design for Venus Deep-Atmosphere Aerobot Operations," to be submitted to AIAA Aerospace Sciences Meeting, Reno, Nevada, January 12–15, 1998.
15. Crisp, D., JPL private communication, Jet Propulsion Laboratory, Pasadena, California, January 1997.