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Planetary Aerobots: A Program for Robotic Balloon Exploration

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Abstract

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 mobile vehicles that operate on the surface and in its 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 robotically-controlled and autonomous balloons - aerobots - and their use in planetary exploration.

Conceptual designs of aerobots capable of vertical mobility in planetary atmospheres using altitude control systems are discussed. The use of prevailing wind patterns to enable global exploration is also examined. Emphasis is placed on the discussion of approaches to autonomous navigation for achieving desired latitudes and longitudes in planetary atmospheres using on-board flight dynamic models and a combination of real-time sensory perception (surface topography, balloon state and atmospheric conditions) and periodic independent position updates.

The design of a planetary aerobot testbed vehicle is described which will conduct a series of terrestrial technology demonstrations which: 1) move gradually from manual teleoperated control of the robotic vehicle to fully autonomous altitude change and landings; 2) achieve increasingly long-range mobility from widely separated launch and landing sites (first predicted sites followed by designated sites). The missions that may use this technology include both scientifically motivated missions and technology demonstration opportunities at Venus, Mars, Titan and the outer planets.

Introduction and Background

At the Jet Propulsion Laboratory (JPL), we are now involved in planning and developing technology for the next phase of planetary exploration using buoyant vehicles. This phase will draw on the technical experience of earlier missions but will employ telerobotic and autonomy technologies to control motion in all three dimensions. There are significant parallels in these systems to the capabilities needed for mobile surface vehicles. However, there are also significant new challenges in atmospheric exploration that demand distinctly different approaches

The original motivation for developing this new class of buoyant vehicle was to advance the exploration of Venus. Following the exploration of the surface of Venus by short-lived Soviet landers and the Vega balloons, JPL carried out the Magellan mission, which mapped the surface of Venus using radar sensors. The radar revealed a surface with a great variety of structural and volcanic features. There has been no clear pathway, however, to follow up the Magellan mission with a long-lived in situ mission.

Venus, Earth's estranged sister planet, has a dense atmosphere exceeding 92 bars in pressure and surface temperatures in excess of 460°C (733 K). Its surface is obscured from view at visible wavelengths by high-altitude haze and clouds as well as the molecular scattering of the clear atmosphere beneath. The Soviet Venera landers were able to function for less than two hours exposed to the high-temperature environment on the Venus surface. With advanced thermal techniques and the use of vacuum insulation, it may be possible to extend surface lifetime to a few days. Much longer lived systems, however, will require radioisotope power and temperature control systems which will be costly and present Earth environmental concerns.

An aerobot on the other hand can turn the environmental challenges of Venus to advantage. The Venus Flyer Robot (VFR) concept, conceived at JPL in 1993, could make brief excursions to the hot surface environment of Venus to acquire data and return to higher altitudes to cool down and telemeter those data to an orbiting relay station or directly to Earth. This concept takes advantage of new technologies in lightweight and low-power electronics and instruments for rovers that were developed at JPL. However, in the case of the Venus aerobot, the attributes of low power and mass are even more critical.

The need for a lightweight payload and control system on an aerobot is obvious. The need for low power is also apparent; but for Venus exploration, it has a significant new dimension. The lifetime of a thermally insulated gondola in the Venus lower atmosphere is limited not only by heat leaks from the high-temperature environment, but also by power dissipated by the electronics. The power required for information acquisition systems can be reduced substantially. However, the power for communications systems is beginning to approach theoretical limits and must be much larger. Hence a strategy of acquiring data near the surface and telemetering it from a higher altitude, where it is cooler, makes practical sense.

Although the original motivation for the aerobot was for Venus exploration, these vehicles are becoming recognized as powerful tools for exploration of all planets with substantial atmospheres. While the short lived entry probes to be deployed on the Cassini and Galileo missions sample the planetary atmosphere at only one place and one time, long-lived aerobots can circumnavigate the planet many times, change altitude and access different latitude zones. Planetary aerobots represent the same kind of advance in exploration potential over single-shot entry probes that planetary orbiters bear to planetary flyby spacecraft. They are also engaging mission concepts that will capture the imagination of the public by their ability to explore hitherto inaccessible regions of our solar system.

Buoyancy and Buoyancy Control

Eight solar system bodies have sufficient atmosphere for exploration with buoyant vehicles. They include the four major planets - Jupiter, Saturn, Uranus, and Neptune; the three terrestrial planets - Earth, Venus, and Mars; and Titan, the satellite of Saturn. Aerobots are lighter-than-air vehicles that include a primary buoyancy system for supporting the mass of the scientific payload, communications, and a closed-system reversible-fluid buoyancy-control system. In this section, we describe the primary buoyancy and buoyancy-control approaches applicable to exploration of the eight solar system targets. A series of Earth demonstrations of reversible-fluid buoyancy control that were conducted during the last year are also discussed. In addition, the method by which buoyancy controls altitude and enables horizontal mobility is described.

Primary Buoyancy Systems:

Although heavier-than-air vehicles have been considered for planetary exploration, lighter-than-air vehicles have clear advantages. First, they are much more suitable for long-duration flight because they can remain aloft without consuming energy. Their lift derives from the displacement of the atmosphere by a lighter gas in a balloon envelope. Heavier-than-air vehicles, in contrast, must generate lift by consuming significant amounts of energy. For a long-duration aerovehicle, a renewable source of energy such as solar power is needed. Solar-powered aerovehicles have, been examined for operation at Mars. Solar-powered aircraft might also operate at Venus above. the cloud layers but would be unable to penetrate the deep atmosphere, which is the region of primary interest. For the outer planets and Titan, the low solar intensities render solar-powered aircraft impractical.

"There are two general approaches to a primary buoyancy system for lighter-than-air systems: inflation with a gas that is inherently less dense than the surrounding atmosphere or inflation with gas from the surrounding atmosphere whose temperature is raised to lower its density.

Light Gas Buoyancy: Mars, Venus, and Titan all have solid surfaces with atmospheric pressures ranging from less than 1% of that of the Earth to 100 times higher (at Venus). Like Earth, these atmospheres are comprised primarily of carbon dioxide or nitrogen, which have comparatively large molecular weights that determine their inherent density. Inflating the primary balloon with a very low-density gas such as helium or hydrogen is practical. Ammonia or water are also satisfactory in the dense, high-temperature Venus environment.

Hot Air Buoyancy: The biggest problem with flying light gas balloons at the outer plane.ts is that their atmospheres are dominated by the lightest known gas, hydrogen (Table 1). A recent study at JPL has shown that just floating a 10-kg payload in the Jupiter atmosphere (without any buoyancy control system), would require about 1000 kg of delivered entry mass, including the necessary hydrogen, cryogenic superpressure composite tanks, phase change ammonia fluid, balloon envelopes, entry module, etc.

Table 1. Abundance of primary species in the outer atmospheres of the giant planets

Constituent	Peak mixing ratio (by number) or upper limit			
	Jupiter	Saturn	Uranus	Neptune
H_2	0.90	0.97	0.82	0.79
HD	5×10^{-5}	3×10^{-5}		0.18
He	0.10	0.03	0.15	0.02
CH_4	2×10^{-3}	2×10^{-3}	0.025	
NH_3	2.5×10^{-4}	2×10^{-4}		
H_2O	3×10^{-5}			
Average Molecular Weight	**2,25**	**2.10**	**2.64**	**2.62**

By definition, a buoyant gas must be less dense than the surrounding atmosphere in order to displace enough air to provide the lift necessary to float a balloon envelope and gondola. One method of achieving this low density is by heating ambient atmosphere. Heating of ambient air can be accomplished by burning a fuel, as in the case for recreational hot air balloons; applying solar energy to the balloon envelope, which heats the internal gas; or by trapping infrared (IR) radiation, inside a balloon envelope which acts like a greenhouse. On Earth, Venus and the Outer Planets there is sufficient IR radiation upwelling from the both.r surface or lower atmosphere to support a properly configured balloon. Such a balloon is called an Infrared Montgolfiere (IRM) after the French originators of the hot air balloon.

The outer part of an IRM upper hemisphere of the balloon is made highly reflective to infrared radiation; the inner surface highly absorptive.. As a result, infrared radiation from below is absorbed by the balloon and raises the temperature of the enclosed gas. This concept, which originate.d in France as the infrared Montgolfiere balloon, has been demonstrated on the Earth in a series of flights (Malaterre, 1993). Exploration of the outer planets to pressures greater than 10 bars, where temperatures are in the vicinity of 300 K appear feasible; measurements made by the Galileo entry probe when it enters Jupiter later this year may confirm its feasibility for that planet.

JPL studies have shown that a very promising, lightweight controllable balloon system using planetary radiation heating, appears quite feasible for the outer gas planets, as well as for Venus. The technology is based on a modification of a design that was demonstrated by a series of 30 infrared Montgolfiere balloons flown in the Earth's stratosphere in the 1980s and 1990s by the French space agency CNES [1]. The balloons' upper surfaces were aluminized to minimize radiant heat loss to space, while their inside upper surface was blackened (?) to absorb 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. Montgolfiere brothers who flew the world's first hot--air balloons (heated by burning wood) in France during the 18th century.

Recent analysis has shown that infrared (, IR) balloon heating technology appears very relevant for missions to the giant gas planets (Jupiter, Saturn, Uranus, and Neptune) as well as to Venus. The increased convective hydrogen cooling of the outer gas planet balloons appears to be more than compensated by the. increased radiative (which is portional to T^4) heating from the lower altitudes of the hot gaseous planets, thus allowing operation at altitudes of about 1 bar and lower. A sketch of the French Infrared Montgolfiere balloon system is shown in Figure 2. 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 Figure 3 as a function of time of day (lowest at night) and cloud cover (higher albedo).

Table 2 summarizes the preferred means of primary buoyancy for planets which have atmospheres which can support balloons and their payloads.

"Table 2. Preferred Means of Primary Buoyancy

PLANET	SURFACE PRESSURE (BARS)	SURFACE TEMPERATURE (K)	PRIMARY COMPOSITION	MOLECULAR WEIGHT	MEANS OF PRIMARY BUOYANCY
MARS	<.01	200 250	CO_2	44	H_2, He
EARTH	1	300	N_2	28	H_2 or He
VENUS	100	750	CO_2	44	H_2, He, H_2O or NH_3
TITAN	1.5	90	N_2	29	H_2 or He
JUPITER	10*	300$^+$	H_2	2.2	Pure H_2 or
SATURN	10*	300$^+$	H_2	?.0	"Hot air balloon" or
URANUS	10*	300$^+$	H_2	2.3	"Infrared balloons"
NEPTUNE	10*	150$^+$	H_2	2.3	

* These planets have no surface; temperatures are shown for the 10 bar-level,
+ Estimates based on model extrapolations. Jupiter will be measured in 1995, Saturn in 2008.

Buoyancy Control Using Reversible Fluids:

Aerobots designed for long-term operation in planetary atmospheres require methods of altitude control that are both energy efficient and involve minimal expenditure of consumables. For planets which have tropospheric atmospheres (like found at Venus, Earth, Titan and the Outer Planets), a closed system reversible-fluid balloon can use the naturally occurring atmospheric temperature decrease with increasing altitude to drive a heat engine, providing the mechanical energy needed for altitude. change.

A reversible fluid is either a gas or a liquid, depending on pressure and temperature. It is this phase change which can be used to control the. buoyancy of a balloon system. When the reversible fluid is in the. gas phase, the balloon has a lower average density than the surrounding atmosphere thus providing a net increase in lift. Conversely, when the fluid is in the liquid phase, the. balloon has a higher average density than the surrounding atmosphere thus providing a negative lift. Figure I illustrates the concept of dual-balloon, reversible-fluid altitude control.

in 1993, JPL began exploring concepts for achieving both the high, cool altitudes for balloon oscillation, and the ability to trap reversible fluids for balloon descent to the surface where scientific observations can be made (Jones 1995), The. first concept considered by JPL used a two-balloon system with the main balloon filled with helium and the secondary balloon filled with a reversible fluid like methylene chloride (heavier than CO_2 as a vapor). The system is designed to be neutrally buoyant when about half the reversible fluid is condensed. Such a balloon would exhibit forced oscillations about an equilibrium altitude of about 56 km at Venus. Descent would be initiated by trapping the methylene chloride in a pressure vessel before the balloon descends below 56 km. The amplitude of oscillation is expected to be a few kilometers above and below the equilibrium altitude. Vaporization is enhanced below 56 km by use of a heat exchanger design, which prevents the system from dipping too low every cycle. The high-altitude oscillation phase can be used to generate electrical energy from solar cells, transmit data to Earth, and recool both electronic packages and phase-change-based heat sink materials (e.g. wax) for later descents to the surface. Opening a valve. releases the gas to refill the secondary balloon causing the system to return to altitude.

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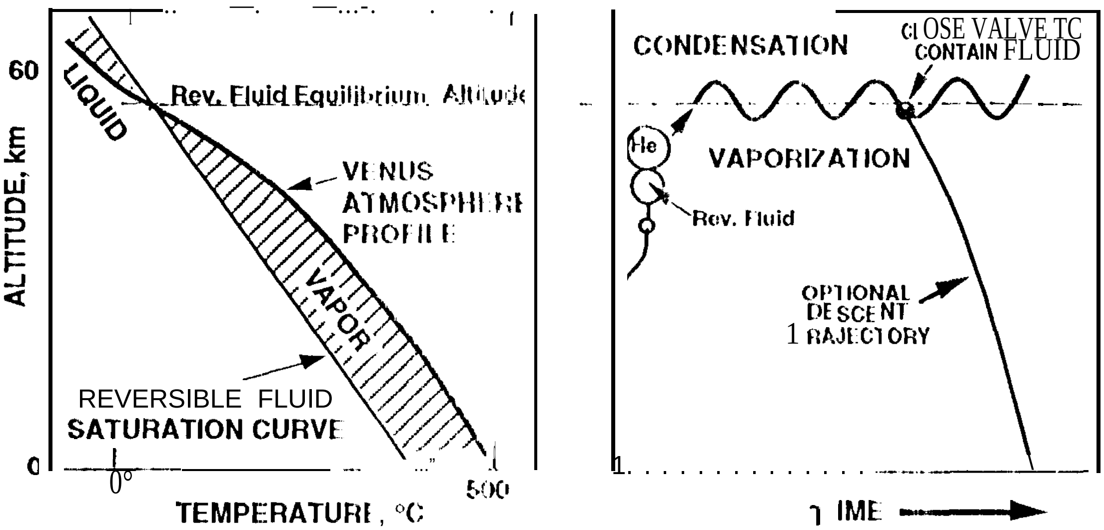

Figure 1 Concept of dual balloon, reversible-fluid altitude control.

Phase change balloon aerobots had previously been evaluated for use on the atmospheres of the outer gas planets of Jupiter, Saturn, Uranus, and Neptune [1]. Ammonia appears to be the preferred phase change fluid for Jupiter and Saturn, with a stabilization altitude of shout 10 bar, while methane appears optimal for Neptune (10 bar) and Uranus (4 bar).

Reversible Fluid Buoyancy Control Limitations

Although reversible-fluid altitude controls is an extraordinarily powerful technique, it has some limitations. One is its inability to modulate the rate of descent to a planetary surface except by evaporating fluid. The use of variable geometry surfaces might augment this capability by allowing an increase in nominal descent rate. A second limitation is that reversible fluid altitude control only works in planetary tropospheres where temperatures drop with increasing altitude and where reversible fluids can be used that change phase within the altitude range that is to be explored. This is the case for the tropospheres of Venus, Earth, Titan, and the outer planets. However, reversible-fluid altitude-control techniques cannot be used in planetary stratospheres where atmospheric pressures are low and the temperature changes very little with increasing altitude, and can even increase. For example, the thin atmosphere of Mars has no troposphere, in effect prohibiting the use of reversible fluids for altitude control. Accordingly, other approaches to reversible altitude control are needed, such as reversible chemical reactions with the atmosphere.

Robotic Balloon Capability

What is an Aerobot?

The concept of robotic aerovehicle or "aerobot" is a powerful new approach to in situ planetary exploration. We distinguish an aerobot from a conventional balloon when it has one or more of the following four characteristics:

1. The ability to autonomously determine its position, altitude, and velocity without intervention from the ground or by a support spacecraft.

2. The means of executing, cyclical altitude variations about a mean altitude in the atmosphere.

3. 'I-hc capability of controlling altitude and executing a designated flight path within the atmosphere.

4. The capability of landing at a designated surface location.

Using Altitude Control to Achieve Lateral Mobility

By controlling vertical mobility, aerobots can select altitudes where wind speeds and directions provide a wide range of horizontal mobility. 'l'his is especially true at Mars and Venus where the occurrence of altitude variable wind gradients enables near-global planetary access.

The 1985 Vega balloon experiments explored the. Venus middle cloud layer at 50-55 km altitude. Vertical winds were found to be large (3 m/s) and variable, with turbulent episodes lasting about an bout. East-to west average zonal winds of about 69.4 m/s for Vega 1 and 66.0 m/s for Vega 2 were detected. Both Vega balloons drifted about 11,000 km from the local midnight meridian into the late morning, sky, carried by strong, predominantly zonal east-west winds.

Vega 1 initially encountered weak southward winds, which changed to northward winds later in the mission. These meridional (north-south) winds produced north-south displacements in the Vega 1 trajectory that never exceeded 50 km. The Vega 2 meridional winds were consistently northward with a mean velocity near 2.5 m/s (Crisp et.al. 1990), which produced more than 400 km of displacement toward the north pole.

The zonal (east-west) wind profiles as a function of altitude shown in Figure 5 were obtained from the several Venus probes and landers (Moroz 1994). These profiles indicated that above 10 km altitude there is a monotonic increase in zonal wind velocity with increasing altitude up to near the top of the. clouds (~70 km). observed variations among the different data sets are possibly due. to variations in probe entry position, according to the local time of day on Venus, anti the phase of a wave motion that circles the planet with a 4-day period. These variations illustrate the. need for better information on the global atmospheric circulation and is the. objective of a future Venus mission.

One postulated model for the circulation of the atmosphere of Venus (Schubert 1983) appears in Figure 6. On Venus, the atmosph writ and sut-face temperatures at the poles are very little different from those at the equator. Since Venus is a slowly rotating planet, the transport of heat from equator to pole is believed to involve a series of Hadley cells. Early balloon flight experiments in the Venus winds will be needed to characterize the parameters of the circulation and will provide the knowledge necessary to use these winds for global mobility in more sophisticated surface reconnaissance missions in the deep atmosphere.

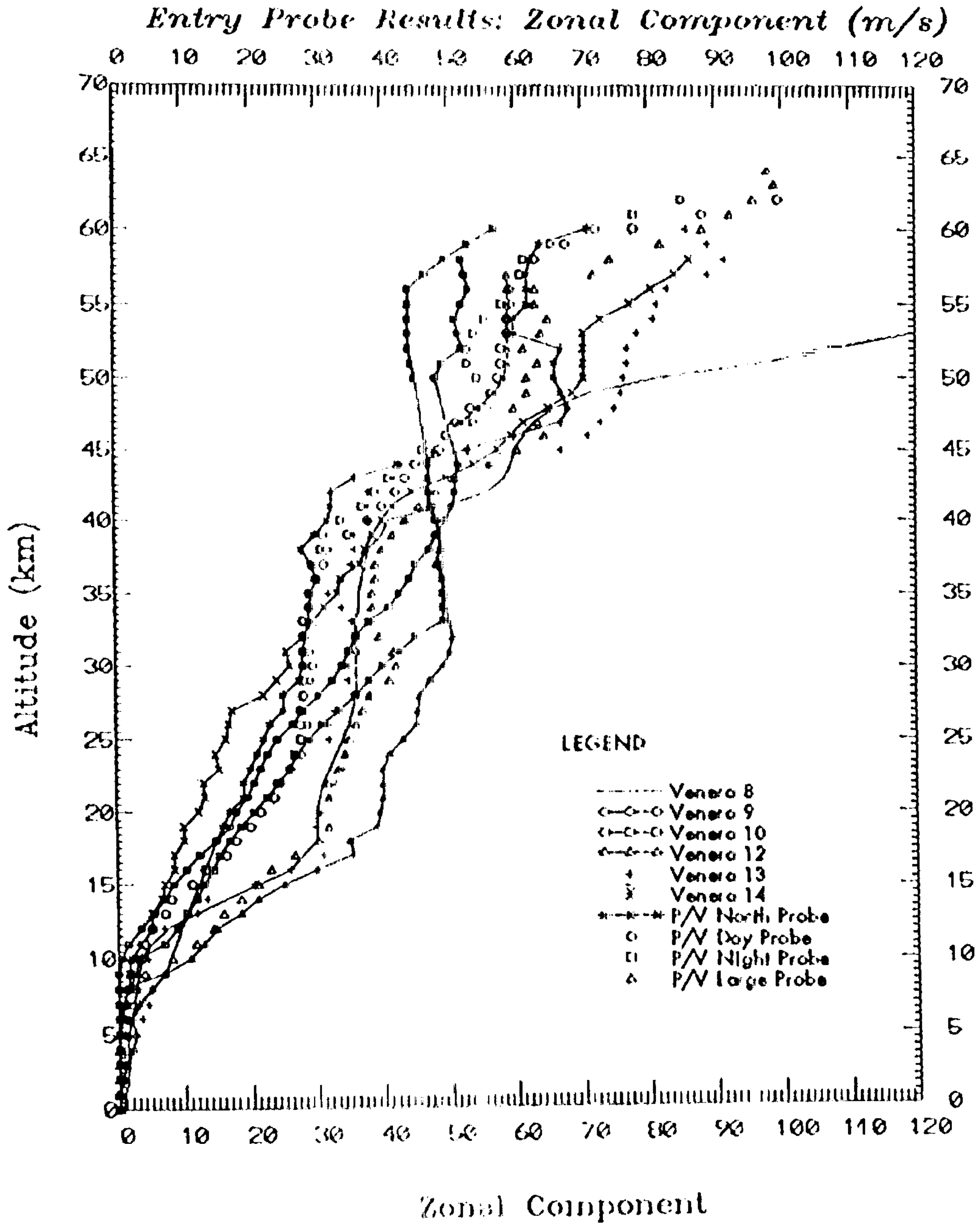

Fig. 5. Venus Wind Profile

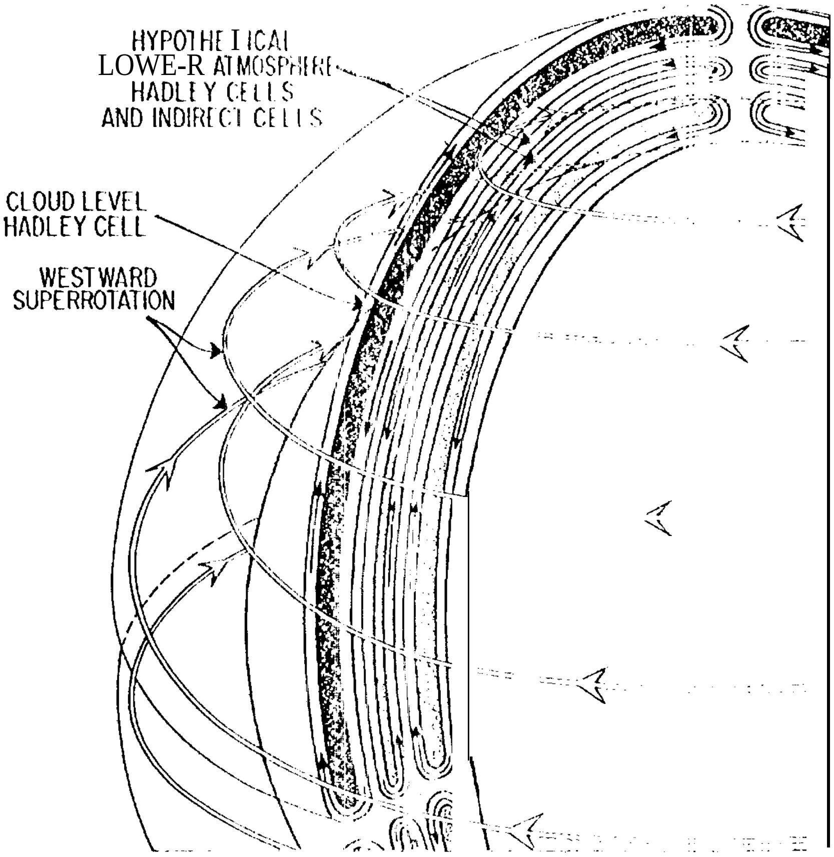

Fig. 6 A. Postulated Venus Global Circulation Model

Soft Landing

Soft landing of science payloads on planet surfaces is achieved by means of a flexible and possibly robotic landing "snake' tethered below the vehicle. As the snake contacts the surface, it relieves the vehicle of some of its gravity load. This enables the gondola to "hover" at a fixed distance away from the surface without impacting it.

Navigation, Control, and Mission Planning

Autonomous State Estimation. An on-board autonomous estimate of position is needed for all of the future aerobot missions. The state variables that would be estimated include position, altitude, velocity, and angular velocity. Not all of these will be needed in a given aerobot mission and the accuracy required may vary from mission to mission. For those missïon concepts that do not incorporate active altitude control an Autonomous State Estimator (ASE) enables remote sensing targets of opportunity to be identified from an on-board prioritized target list. For those missions that have active altitude control and the potential for modifying, the flight path it provides the essential data for navigating a desired flight path. For those missions involving landings, additional capabilities will be needed for the terminal descent phase.

Radio metric position and velocity measurements can be made by observing the aerobot radio signal from the Earth or from a communication relay orbiter. These measurements will not usually be available continuously and the results must be communicated to the aerobot before they are useful. In addition, for radio metric measurements made on Earth, there will be a significant delay in measurement associated with the round-trip light time. Accordingly, an ASE relying on aerobot sensors, is necessary for timely and complete information for targeting and/or flight path control.

On-board sensors could include. solar or star trackers, surface imagers, surface radar range/Doppler sensors, magnetic field sensors, and inertial sensors. Tracking an orbiter radio beacon from the aerobot (similar in concept to Earth - based GPS systems) to determine the aerobot's state variables, is another option. The sensors and associated signal-processing electronics must be compact and require very low power in order to be accommodated on the aerobot.

Output of the ASE is provide.d to the controller of the remote-sensing payload which enables the acquisition of targets of opportunity from a prioritized target set stored in the aerobot memory.

For Venus missions, the cloud-shrouded atmosphere makes celestial references impractical, but surface referencing is attractive. Imaging in the infrared region of the spectrum yields maps of surface temperature that correlate strongly with altitude. It is possible to match these data with a low-resolution map of Venus topography obtained by the Magellan mission. Monitoring the radio metric parameters of a known radio beacon of an orbiter provides further information that can be used in the velocity estimator process. Velocity measurements can be acquired from frame-to-frame correlation of repeated images as the aerobot drifts over the surface. For both measurements, gyro and accelerometer measurements of the rotational state of the aerobot can be used to establish the orientation and pointing, of the sensor.

For a Mars mission, the absense of clouds in the atmosphere makes celestial references (Sun, stars) practical although the occurrence of dust storms may degrade stellar visibility during both day and night. The use of a simple Sun "sextant" sensor has merit. This sensor idea is attractive because the location of the aerobot can be constrained by measuring the elevation of the Sun at a known time. A definitive. positional measurement is feasible if the solar azimuth can be measured with a stable azimuthal reference. Simultaneous measurements with an imaging sensor during, the day could be used to determine velocities with a similar approach to that discussed for Venus.

For Titan, the Cassini mission is expected to provide radar maps similar to those already obtained for Venus by the Magellan mission. However, thermal imaging of altitude at Titan by the aerobot, is impractical due to the extremely cold conditions. Radar altimetry, visible imaging or "Saturn" sensors may permit positional referencing to the radar map, but they have not been studied. Velocity measurements could be acquired with Doppler radar or with repeated correlated visual imaging.

For outer planet missions, with no surface references and no access to celestial references, other sensing approaches are needed. Fortunately, all these planets have strong magnetic fields offset from their rotation axes. This should enable measurements of both latitude and longitude to be made with useful precision as well as providing the azimuthal orientation of the aerobot sensor platform.

The preceding discussion of sensors was primarily in the context of global positioning and navigation. When landing aerobots at designated landing sites, reference to detailed surface topography or imaging of the target area and its surrounding is needed. Accordingly, a referenced database would be loaded in the aerobot prior to the terminal descent phase.

Requirements for On-Board Sensor and Perception System

One of the critical capabilities that an aerobot will have is that of on-board localization of the aerobot with respect to the planet, a knowledge of the vertical and horizontal aerobot motion, and the determination of the attitude of the gondola on which the various scientific instruments may be mounted. An on-board sensor and perception system would provide these capabilities in support of global navigation and path planning, descent and landing operations, and science instrument pointing. The system basically would answer the following questions from the point of view of an fictitious observer riding. on the aerobot: where am I; where am I going; and what am I looking at? In order for the. aerobot to develop such an understanding of its location and orientation, it must carry within its on-board computer a hierarchy of sensors and state estimation algorithms:

1. Vertical Motion Determination: This is a Kalman filter which takes pressure and vertical air-speed measurements, combines these with a relatively simple on-board model of the aerobot up and down motion, and produces a continuous estimate of how high the aerobot is with respect to a selected reference altitude.

2. Platform Attitude Determination: This is a filter which takes accelerometer and angular rate gyro measurements, combines these with a simple pendulum-like model for the platform attitude dynamics, and produces continuous estimates of the platform attitude and its angular rates. This estimator is used to trigger the science camera to acquire science images at low-rate instants, and to acquire navigation images at nadir-pointed instants.

3. Inertial Translation Determination: This filter takes accelerometer and rate gyro data, combines these with a simplified translation dynamics model, to propagate the lateral position of the aerobot under "blind" conditions in which direct measurements of the aerobot position are available.

4. Ground Track Determination: This is a filter which takes localized wind-models, together with successive image and pointing information, in order to estimate the ground track velocity and position. The imaging correlation is augmented by using the inertial sensor predictions emerging from the inertial translation determination process above, in order to simplify and improve. the accuracy of the resulting ground track estimate.

5. Global Navigation Updates: To provide global knowledge of the aerobot location, in a coordinate system attached to the rotating planet surface, an estimator that carries the aerobot location as its primary states is under development. This esimator monitors global events such as crossing of the terminator between night and day. Other type of data could be a doppler beacon profile from an orbiting satellite. The global update could also come from an Earth-based VLBI approach, although this would impose additional requirements on the hardware to be carried on-board in order to provide such a capability.

Typical Scenario. The typical scenario in which all of these capabilities would work together is as follows. The vertical motion estimator would be operating all the time, and would therefore be operating at the smallest time scale. As the aerobot dips low into the atmosphere as part of a deep oscillation, the vertical estimator triggers start of the ground imaging based on the velocity estimate. The inertial sensor attitude and attitude rates are then used to trigger a sequence of navigation and science images. Ground track velocity estimates are refined as the aerobot passes its lowest descent point and begins climbin up. Ground imagery loses quality, and the aerobot switches to a purely inertial means of determining its lateral position. As the aerobot ascends, sun-sensor data (if such data is available) may become more directional and is used to estimate aerobot planetary position. An orbiter beacons is detected. The shape of the doppler frequency changes from initial acquisition of frequency to loss-of-signal constrains the aerobot position. The terminator crossing provides similar information. Error covariances are marked down, and the filters are re-initialized. Previous data is run "backward" through a data smoothing algorithm in order to refine earlier position estimates.

Such a scenario, while relatively easy to describe, presents significant technical challenges. The single major challenge is due to the uncertainty in the global motion of the aerobot as it moves over the planet surface. On-board models for aerobot motion and for wind are likely to be accurate only within a relatively short spatial scale. The error covariance of the aerobot position estimates are likely to grow rapidly, in the absence of direct measurement data of the aerobot position. On the other hand, such direct estimates are not easy to acquire.

Altitude Control and Navigation. An on-board Altitude Control and Navigation (ACN) system guides the aerobot to a desired location above or at the planetary surface. The ACN system receives the location of a desired target expressed in latitude, longitude, and altitude coordinates from a ground station on Earth.

This target-site-location information is processed by a global trajectory generator (GTG), which predicts a flight path that the aerobot must achieve in order to get to the desired terminal descent entry corridor and generates a command list for the altitude controller that is designed to realize this flight path. The GTG uses a simplified on-board atmospheric model based on the best available information (global circulation model) about prevailing wind conditions at various altitudes and a model of the reversible-fluid altitude-control system. Other inputs to the GTG are thermodynamic parameters of the ambient atmosphere and the altitude control system from on-board sensors and the initial location and velocity of the aerobot from the ASE.

Inevitable uncertainties in the wind model mean that the. predicted flight path will have significant uncertainties. The ACN system compares the predicted flight path with the actual flight path from the ASE and, when deviations exceed a prescribed threshold, issues commands to the flight controller to update the flight path so that the aerobot achieves its targeted destination. Changes to the profile will not be made continually but only at a small number of discrete points in the trajectory.

An altitude controller is at the core of the overall altitude control and navigation systems. Control in altitude is essential to achieve controlled trajectories over the planetary surface. Semicontrolled movement lateral to the uncontrolled flight path is achieved by combining altitude control with knowledge of the wind direction as a function of altitude. Results discussed earlier suggest that on Venus, for example, the circulation is inherently more predictable than that of the Earth. However, the wind models will inevitably have significant errors, and the accuracy of the resulting aerobot trajectory will degrade as it is projected further into the future.

Aerobot navigation is a very different class of guidance-and-control problem than is faced by the navigator of a spacecraft who deals with highly deterministic gravitational effects and well defined control impulses. Fortunately, the aerobot will have more than one opportunity to perform the maneuver needed to view targets or to reach a terminal descent region. Several circumnavigation trajectories may be necessary to gradually reduce the trajectory errors and reach the designated destination.

While the goal of controlling the trajectory and landing location of a lighter-than-air vehicle is challenging, a promising precedent exists in terrestrial teleoperated balloon experiments in the 1960's which have used helium venting and ballast dropping for altitude control. These experiments were motivated by atmospheric scientists interested in examining more than one vertical slice through the atmosphere and by engineers interested in using balloons as missile targets. (Gildenberg, 19"/(1).

Aerobot Operations. In this section, aerobot capabilities are examined that can enhance the exploration potential and the scientific return from a mission.

1.) observing Targets of Opportunity A conventional planetary balloon mission, makes observations that are essentially random along a poorly known flight path. An aerobot, equipped with a basic capability for autonomous position determination, can provide a major gain in balloon capability by being able to observe targets of opportunity.

As previously discussed, ASP output can be made available to the controller of the remote-sensing payload, which also has access to the locations of a prioritized set of targets of opportunity stored in the aerobot main memory. In this way, scarce data-return resources (storage and telecommunication) are only allocated to the highest priority targets traversed by the aerobot

Even without an ability to change flight path, this method represents a substantial increase in capability over a conventional balloon. In the case of a free flight reversible fluid balloon which executes cyclical altitude variation, an additional condition for data collection would be the altitude at which data are acquired. Images from the lowest points in the aerobot trajectory would be expected to be of much higher quality than data from higher altitude.

This level of vehicle control can also be used to deploy small instrument packages to the surface of planets provided the change in buoyancy can be accommodated or even used in lieu of a reversible altitude-control system.

2.) Control of Flight Path: The goal of flight path control is to maneuver the aerobot from its initial 3-D atmospheric location to an approach position where low-altitude observations of a designated target can be conducted or landing operations can begin. Periodic command and navigation updates will be required. For planetary aerobots, communications are possible only when the aerobot is on the nearside of the planet unless an orbital relay satellite is used. Even then, communications may be limited. For an aerobot in the upper atmosphere winds of venus 50-60" km altitude, the Earth is out of view for 3 to 4 days during every 6 to 8 days "orbit" around the planet.

The aerobot uses a simple on-board wind pattern model for trajectory generation. This wind model is analogous to the world model embedded in a conventional robot to map obstacles. An aerobot's wind model captures planetary wind behavior in terms of prevailing wind directions, wind velocities vector directions as a function of altitude, vertical down/up drafts caused by winds passing over the surface caused by topography, cloud-cover, and day/night insolation models. These comprise relatively simple computer models suitable for on-board use and are not complex meteorological models.

Data from prior planetary missions, e.g., Venus (Crisp et al., 1990), provide a start for such models. Challenging maneuvers include long longitudinal traverse, equator crossing, and latitude change. Initially, there will be large uncertainties in global navigation. Early efforts will therefore focus on reaching regions of fairly large size, or of reaching targets of opportunity, instead of trying to achieve pin-point landing at specific sites.

3.) Terminal Descent Strategy. For a Venus aerobot, terminal descent starts at a corridor upwind of the desired landing site. For Venus, previous Venera and Pioneer Venus probes have determined a vertical profile in wind speed ranging from about 100 m/s at about 65 km to near zero at the surface (Crisp et.al. 1990). The current uncertainty in wind velocity profiles is about 20%.

Uncontrolled descent only lands the vehicle somewhere along its wind-driven path. Controlling the descent rate allows the target to be achieved, provided wind and thermodynamic profiles are nominal and the descent start corridor is chosen correctly. To land at the required target, the nominal descent rate is matched with the expected horizontal wind velocity. A more advanced approach uses on-board sensors to iteratively estimate the likeliest landing point, and continually adjust the descent rate to guide the vehicle to the prescribed site. This increases the reliability of achieving the target along the wind-driven path, but also increases system complexity. Controlled descent is particularly challenging with reversible-fluid altitude control since the mobility mechanism available to the robot as it goes down is one-sided. The descent rate can only be made slower, not faster.

Venus Aerobots

Although more than 20 missions have flown to Venus in the last 30 years, the exploration of this "sister" planet to Earth is still in its initial stages. The harsh Venus environment has prevented any intensive exploration of the surface and deep atmosphere. Venus is the only planet which has been explored with aerovehicles. It is an attractive target for future aerobot missions because of its harsh, high pressure, high-temperature environment. An aerobot can enable many kinds of observations which may be impractical to obtain by any other means. Robotic balloon vehicles may have an important role in the post-Magellan exploration era. A Venus robotic balloon or aerobot has been identified by NASA as a high-priority candidate for the next mission to explore the Venusian surface and lower atmosphere. The high surface temperatures (740 K) and pressures (95 bars) are a challenge to space systems and science instruments. These conditions also present an opportunity to exploit the energy available from the large temperature difference between the surface and the upper atmosphere. Venus aerobots will use the hot Venus surface heat to evaporate fluids to fill a balloon on the surface, thus assisting ascent to the cool upper atmosphere. The electronics will then be cooled and the balloon fluid will condense, allowing re-descent of the balloon system. A Venus aerobot vehicle spends most of its life in the upper, cooler atmosphere with frequent, short excursions near or to the Venus surface for scientific investigations. This paper will describe Venus aerobot/balloon mission and system concepts and the important measurements which can be made from this new type of low-cost long-life, *in situ* exploration vehicle.

Global radar mapping by the Magellan spacecraft has provided the first comprehensive assessment of the geologic characteristics and evolution of the Venus surface, identifying a wide range of volcanic features and tectonic landforms. On Earth, radar data are commonly combined with complementary information acquired in the visual part of the spectrum. The lack of these data for Venus, along with the moderate, ~100 m, spatial resolution from Magellan, raise many questions regarding the geology of the Venusian surface and the interpretation of the radar data. The Venusian atmosphere and surface temperature and pressure pose unique challenges for imaging the surface because the density of the atmosphere, coupled with its constituents, restricts the altitude at which visible imaging is useful. Aerobot imaging concepts are being studied which can obtain imaging in the near IR (0.95 to 1, 1 microns) at high altitudes, where the visibility is relatively good at these wavelengths, and in the visible part of the spectrum (-0.7 microns) very near the surface (<5 km).

The atmospheric composition of Venus and the nature of surface-atmosphere interactions remain as significant science issues. We currently have no information on the chemical composition of the atmosphere below 20 km altitude where over 80% of the atmospheric mass resides. Several fundamental scientific questions relating to atmosphere chemistry and surface-atmosphere interactions can be addressed by *in situ* measurements by suitably instrumented aerobots including 1) What is the mineralogy of the surface? 2) What is the chemical composition of the lower 20 km of the atmosphere? 3) What is the oxidation state of the surface'! 4) What is the identity of the high dielectric materials (metallic snows) present on high elevations" and 5) What is the nature of the sulfur cycle that is responsible for the global cloud cover '! Instrumentation concepts are being developed for use on aerobots which can make measurements of" atmospheric chemistry in tbe lower 2.0 km.

Two big questions relating to the atmospheric structure of Venus are 1) What causes the superrotation of the atmosphere'! and 2) What is the nature of' the Venus greenhouse? The atmospheric circulation in the lower 20 km is very important to the answering of these questions. These questions can be addressed by making measurements in lower atmosphere of temperature profiles, vertical and horizontal winds, and optical properties like solar and IR fluxes. 1.OJlg-life aerobots can make periodic and systematic soundings from the 60 km to surface at a variety of latitudes and longitudes and at different times of the Venus day in order to make these important measurements.

Balloon Experiment at Venus (BEV). An inexpensive flight demonstration of reversible-fluid altitude control, called Balloon Experiment at Venus (BEV) has been deve.loped as a possible piggyback to a NASA Discovery Program mission (DiCicco et al., 1995). The BEV flight demonstration would refine on-board navigation designs by characterizing the robotic vehicle and on-board sensor operation. It would relay data acquired with a mapping sensor directly to Earth.

The BEV system is designed to be a passive, free-fli@t balloon which uses ammonia as the primary buoyant gas and water as the reversible fluid (o enable altitude cycling. Figure X illustrates the operation phase of the balloon system which could oscillate indefinitely from 60 km to 40 km or perhaps as low as 20 km in altitude depending upon balloon envelope material heat resistance.

Venus Flyer Robot. This aerobot would incorporate all four of the aerobot attributes previously discussed. It would use autonomous navigation and control to enable repeated short observations of the Venus surface over long duration. 'The Venus Flyer Robot (VFR) would conduct remote-sensing visual and infrared-imaging observations from the middle atmosphere and make brief excursions to the surface to sample the surface and near-surface atmosphere using a balloon envelope capable of operating at those temperatures (Yavrouian et. al., 199S). To achieve global maneuverability, the VFR would exploit its altitude-c.o)ntrol capabilities to access regions of the atmosphere with favorable north-south winds (Cutts et.al , 1995). Using autonomous navigation capabilities and these winds, VFR could move to particular site.s of interest to make remote observations and to land

The VFR would use a water/ammonia buoyancy system similar to BEV except that in the case of VFR the vaporization of water would be controlled. The system would cycle at high altitude until it senses the approach to a targeted landing site when the VFR's buoyancy control system would contain the water in a pressure vessel allowing the vehicle to descend to the surface for science operations. Figure Y describes a typical operation profile.

A Venus aerobot has been identified by a NASA science group as a high-priority candidate for the next mission to explore the Venusian surface. Maat Mons, a volcano 8 km above the mean surface level that is about 60 K cooler than the mean surface temperature, has been proposed as a site of scientific significance and accessibility.

Titan Aerobots

Saturn's largest moon Titan orbits once every 16 days at an altitude of about 1.2 million kilometers above the atmosphere of this ringed gas giant. Titan's dense nitrogen-organic atmosphere makes it a uniquely interesting object. With a diameter of 5150 km (between the Moon and Mars in Size) it may resemble the Galilean satellites, but its surface is hidden beneath organic haze suspended in a nitrogen-methane atmosphere with a surface pressure of 1.6 bar. (The only other nitrogen-based atmosphere is that of the Earth.) Only about 10% of the sunlight on Titan reaches the surface. Titan's temperature falls off, from the "warm" 94 K found at the surface, at -0.7 K/km to about 73 K at the tropopause near 40 km. The atmosphere is very extended, with a scale height of about 20 km. The winds are expected to be light at low altitudes (circa 10 m/s at 10 km altitude) and flow in a zonal (E-W) direction. Recent images by the Hubble Space Telescope indicate that Titan has a varied surface, perhaps with active resurfacing processes occurring, including ice volcanism, methane rainfall, and pools or lakes of liquid hydrocarbons. Methane at Titan would act as an analog, to water on Earth participating in geothermal, erosive, meteorological and photochemical processes. Figure Z illustrates the environment of Titan.

Naturally, such an intriguing world has received close attention. Despite a close flyby by Voyager 1 in 1980, many mysteries remain as Voyager's cameras could not penetrate Titan's thick haze. However, Voyager data indicated the pressure and temperature structure of the atmosphere and identified many of its constituents. Launched in 1997, the Cassini mission will begin a 4 year tour of the Saturnian system when it arrives in 2004. Cassini will greatly improve our knowledge of the surface of Titan as well as its atmosphere. An ESA parachute-borne descent probe called Huygens will be dropped into Titan soon after Cassini's arrival to analyze the Titan atmosphere and to image the surface. Cassini orbiter radar, infrared, imaging and other remote and direct sensing observations of Titan will be carried out as well as radio occultations on the many Titan flybys currently planned.

Long-duration *in-situ* exploration by a Titan aerobot offers the possibility of greatly enhancing the science return from Cassini investment. In the case of Titan, a reversible fluid like argon is either a gas or a liquid, depending on pressure and temperature. This phase change can be used to control the buoyancy of a balloon system. When the argon is in the gas phase, the balloon has a lower average density than the surrounding atmosphere thus providing a net increase in lift. Conversely, when the argon is in the liquid phase, the balloon has a higher average density than the surrounding atmosphere thus providing a negative lift.

One exciting new mission enabled with this buoyancy technique is a Balloon Experiment at Titan (BETA) which could utilize the Cassini telecommunication relay capability in

Saturn orbit by 2004. This mission would employ advanced telerobotic, materials, microelectronics, sensors and thermal/mechanical technologies. BETA would be the first mobile *in situ* vehicle to explore the permanently shrouded, cryogenic surface and atmosphere of Titan. Figure AA illustrates a typical flight profile of BETA mission which would use argon as a reversible fluid and helium for primary buoyancy.

A Titan aerobot could make. a significant contribution to the exploration of Titan by: 1) characterizing surface morphology at very high resolution below the haze layer and improving and extending the interpretation of ground- based, Hubble Space Telescope and Cassini radar observations; 2) making low atmosphere chemical composition measurements; sampling surface (liquid & solid) chemistry and "mineralogy" at designated sites; 3) contributing to the understanding of global atmosphere circulation by making precise wind speed measurements and 4) performing a global inventory of surface volatiles (estimation of surface layering and the depth of lakes).

Among possible elements in the science payload include a nephelometer/absorption spectrometer (to measure cloud opacity and methane abundance) using laser diodes, imagers (operating in atmospheric windows in the near- infrared) looking down (for wind drift measurement and mapping), sideways (for topography) and upward (for navigation, using the sun and Saturn), advanced solid state detectors (to measure surface chemistry and IR properties) and a simple radio altimeter/sounder to monitor vertical motions and to investigate the surface.

Mars Aerobots

Until recently, the 1998 robotic expeditions to Mars were. to include a French/Russian Mars balloon system. This balloon mission has now been canceled in the wake of the collapse of the U. S./Russian joint Mars together activity for the 1998 Mars opportunity. At the same time, pressure has come to bear on the U. S Mars Exploration Program to keep it exciting by including mission elements that are challenging to the scientists and engineers and engaging to the public. Among the new, interesting options being investigated directly by the U. S. program are robotic balloons.

In general, balloons have high exploration potential including the ability 1) to survey surface morphology at ultra high resolution to obtain insights into surface features and processes such as aeolian activity and volcanism, 2) to search globally for volatiles such as permafrost, 3) to make *in situ* measurements of global circulation, 4) to obtain high spatial resolution IR transects of surface composition and thermophysical properties to use as "ground truth" for global orbital data, and 5) to deploy very simple, lightweight micro-packages at designated site.s along the flight path.

A low-cost Mars balloon mission and system concept is being studied at JPL and its state of technical readiness is being evaluated for a possible U.S. Mars balloon mission for the 2001 mission opportunity. This mission concept is constrained to the use of a Delta-Lite launch vehicle,. The entry systems are based on the hardware currently being developed for the Mars Surveyor lander in 1998 Communications to and from the Earth is by means of the Surveyor orbiters using systems developed to relay lander data. Key assumptions on the mission are the use of 1) a constant density altitude superpressure balloon system without landing capability, 2) a 10 kg gondola with up to 3-4 kg of science instruments, and 3) Mars northern hemisphere entry and fright (the high topography of the southern hemisphere makes balloon deployment and flight there extremely difficult). A possible payload for this mission could include high resolution imaging (10- 20 cm per pixel), thermal emission spectroscopy at 100 m spatial resolution, and neutron spectroscopy to search for subsurface water.

As advanced planning evolves for Mars exploration, the role of aerobots is being defined. Future Mars missions are expected to include longer range rovers and sample return systems. When the surface knowledge requirements for landing from direct entry trajectories and for long range independent rovers are considered, high resolution imaging (25 cm resolution) is high on the list of priorities. From Mars orbit such imaging is very difficult and expensive to obtain requiring large focal length telescopes to be placed in orbit about Mars. 110111 a Mars aerobot, such imagery can easily be obtained at 3-4 km altitude using state of-1111 . . . . art and inexpensive cameras. Imagery from long duration Mars balloon missions are certain to include regions of potential interest to Mars exploration planners.

Jupiter Aerobots

(SCAN IN NEXT TWO FIGURES)

A Jupiter IR Montgolfiere Aerobot (IRMA) concept could use the internal radiated Jupiter IR flux to heat ambient atmosphere that was collected upon initial descent. As in the French IR balloons on Earth, the radiant upwelling of heat would balance the natural convection cooling from the balloon. Radiant heat goes as the fourth power of temperature, and natural convection is proportional to the first power of temperature difference. Natural convection goes as the 1/4 power of pressure, and is thus very little affected at these pressures. Natural convection also goes almost as the inverse of molecular weight, and thus it can be expected to be at least 10 times higher for Jupiter's hydrogen/helium atmosphere as it is for Earth's air.

IR Montgolfiere balloons are heated by radiation from below and cooled by convection to the surroundings. Assuming (a) that an IR Montgolfiere can capture 90% of the lower radiant heat, (b) that a balloon emits no radiative heat to the upper, cooler atmosphere, and (c) that the Jovian atmosphere molecular weight is 2.257, we can calculate the size of balloon that is necessary for neutral buoyancy at any pressure (altitude) for various balloon film thicknesses (Figure 7). Balloon envelope mass is directly related to balloon envelope thickness.

Next, allowing for a 10-kg gondola (science instruments) and an additional 5096 mass above the balloon film mass (for supports, cables, etc.), and we can calculate the total mass of the balloon system in the neutral buoyancy condition as a function of pressure (altitude) and balloon thickness (Figure 8). From this graph, it is clear that we require a thin balloon film (e.g., 0.5 mil). The French flew a similar balloon design for their experiments.

(INSERT FIG 7 & **8** FROM MA'l'rl'111c[!P4)

Two "point designs" for Jupiter Infrared Montgolfiere Aerobots (IRMAs) have been considered and are shown in Table 4. Allowing for a 100% mass increase for entry and deployment system delivery mass, the total entry masses are then 120 kg for 2-bar flotation and about 68 kg for 4 bar floatation. This latter number is about 14 times less than a corresponding pure helium balloon for Jupiter. This difference in Jupiter entry weight can reduce launch vehicle cost from about $200 400M (Atlas/Titan Class) to about $60M (Delta 11 with Kick Stage).

Table 4. Two Jupiter IRMA Point Designs

Parameter	Design #1	Design #2
Jupiter Float Pressure, bar	2	4
Jupiter Float Temperature, K	210	260
Balloon Diameter, m	28.6	19.9
Balloon Thickness, microns	12.5	12.5
Payload Mass, kg	10	10
Total Floating System Mass, kg	59.5	34.1
Estimated Entry System Mass, kg	120	68

One concept for a controllable Jupiter IRMA is to use some type of balloon hot gas venting system, such as that used by hot air emergency descent systems here on Earth. This could be accomplished by means of a self-actuated louver control system that would open at some cold temperature and close at a specific hot temperature. Another possibility is to use a liquid crystal film which changes its IR absorption properties as a function of applied voltage. If placed on the upper inside surface, it could be used to control the amount of lower atmospheric heat that is absorbed. Upward and downward mobility of IRMA could then produce electrical power by means of a wind turbine.

Small, deep atmosphere probes could be dropped from IRMA that reach down to pressures of 500 bar or more. Data could then be transmitted to the balloon and relayed to an orbiting mother ship, which would, in turn, transmit data on temperature, pressure, radiation, gas species, etc. to Earth. Figure 1 illustrates one IRMA concept for exploring the deep atmosphere of Jupiter,

Earth Demonstration Program

Flight Tests of Dual-Balloon, Reversible-Fluid Systems.

Because the Venus high-altitude atmosphere is similar to the Earth's in temperature and pressure, we can demonstrate reversible-fluid altitude control technology in our own atmosphere. Between 1993 and 1995 we carried out a series of five flight demonstrations of reversible fluid control systems. These Altitude Control Experiment (ALICE) tests were performed with purely passive dual-balloon systems using helium and Freon R 114 (Neck, 1995).

In the ALICE project, a very small (total system mass <3 kg) two-balloon system is being tested. The primary balloon is filled with helium and the buoyancy-control balloon is filled with a commercial refrigerant called R114, which is about 7 times heavier than air. At Earth atmospheric conditions, R 114 becomes a liquid above 4000 to 7000 meters depending on weather conditions. A typical ALICE balloon system includes a helium balloon, radiosonde, and a R 114 buoyancy control balloon. Both rubber latex and clear polyethylene helium balloons have been flown. The radiosonde is a slightly modified commercial unit which provides an 8-channel capability for balloon telemetry in addition to measuring normal pressure, ambient temperature, and humidity. The R114 balloon or bag (since it hangs from the system) is constructed from clear, 2-mil-thick, seamless tube of 3-feet-wide lay-flat polyethylene film, which is heat sealed to achieve the proper bag configuration. In the most recent flights, the balloon system is fully instrumented to continuously monitor the temperatures of the helium gas and the R114 as it changes from a gas to a liquid. These temperatures are measured by very small (14x20 mil) thermistors, some of which are painted white and are in protective gold-plated cages to reduce the effect of solar radiation on the temperature measurements.

Extensive balloon performance modeling has been carried out in the ALICE Project in order to characterize the thermodynamics and aerodynamics of the dual-balloon system in a given environment (Wu and Jones 1995). This modeling is based upon extensive experience gained in the NASA Scientific Ballooning Program (Needleman et.al., 1993; Carlson et.al., 1983).

The first two flights were launched during the day and employed standard 200 to 300-g rubber latex helium balloons. In both flights, the balloon ascent rates were seen to slow at a higher-than-expected condensation altitude. However, the balloons did not exhibit oscillatory behavior. Extensive balloon thermodynamic and aerodynamic modeling and balloon envelope thermodynamic parameter testing suggested several problems including higher-than-expected solar heating of the helium balloon (causing greater lift). The third flight began after sunset in order to better decouple model parameters relating to effects of forced convection and drag. This third flight was identical to the first two flights except that the balloon system was fully instrumented to continuously monitor helium temperature and R114 temperature as it changed phase from gas to liquid. After reaching about 6500 m altitude, the balloon descended as predicted by performance model estimates until telemetry was lost at about 2600 m when the balloon went below a mountain range as seen from the receiver station. Re-ascent before impact was predicted to be unlikely for this flight because the equilibrium altitude during the winter was only about 4000 m and the R114 bag did not incorporate a heat exchanger to facilitate liquid boiling,.

"The configuration for the fourth and fifth flights is illustrated in Fig. 3. This configuration had two new features, namely a 0.X-mil clear polyethylene helium balloon and an integrated heat exchanger built into the R114 bag to facilitate fluid boiling at low altitudes. The flight of the fourth mission occurred primarily at night. The total balloon system mass was about 3 kg. Four complete oscillations between 5 and 9 km in altitude were recorded on the fourth flight. These data demonstrated the basic principles of the operation of reversible fluid balloons and allowed us to make important changes to the balloon performance model to better predict the behavior of future systems. one key change was the adjustment of balloon drag coefficients to better correspond to flight experience. Figure 4 shows the mission profile from this flight. The thin line is actual data with the post-flight model fit shown as a bold line. The bottom altitude profile is the topography under the ground track. The middle line shows estimated updrafts and down drafts during the flight used in the model fit. One complete oscillation occurred after sunrise. The "daylight" oscillation was very difficult to fit to the. model without evoking strong updrafts and/or uncertain effect of cloud layers we knew to exist in the vicinity of the balloon. The next step was to fly a balloon, properly instrumented for day flight, in the daytime.

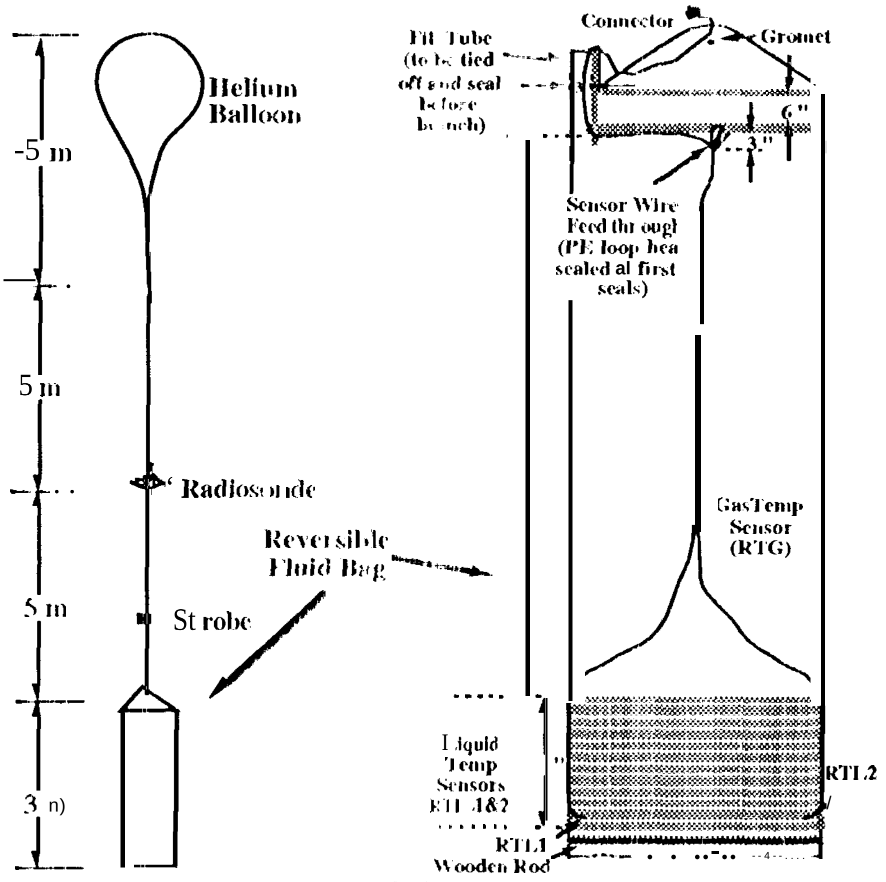

Fig. 3 ALIC '1 ()/1) Flight Configuration

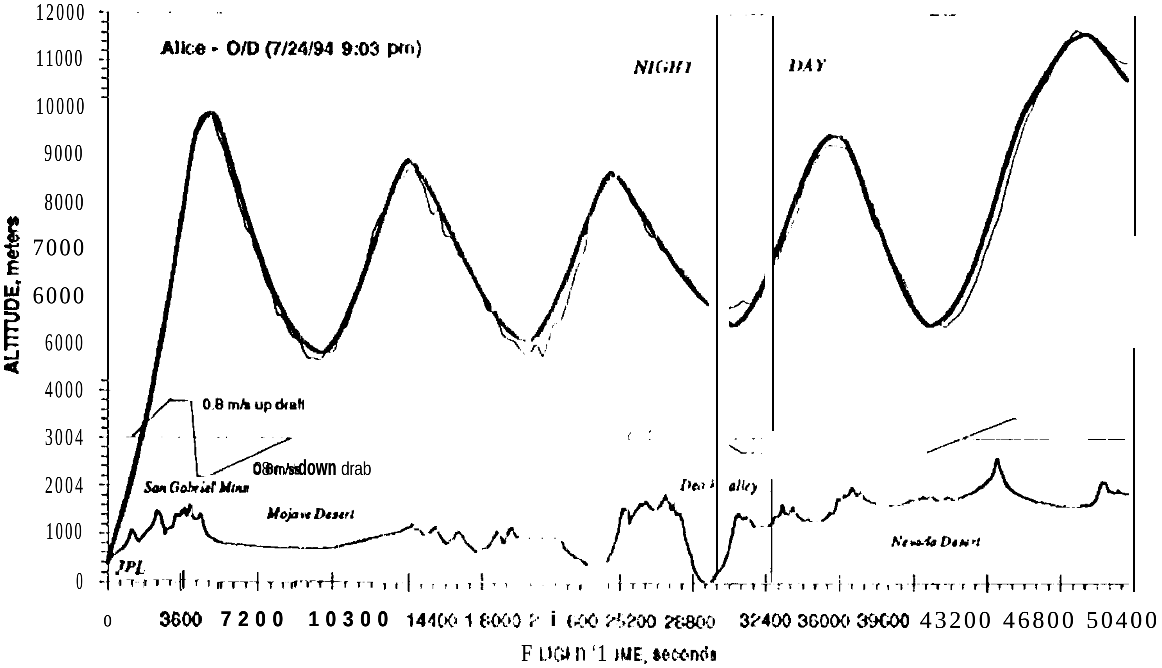

Fig. 4. Actual vs Computer Simulated Data for the Fourth ALICE Flight

The sixth flight of this ALICE configuration occurred on September 30, 1995. The primary purpose of this flight was to test a prototype vertical wind sped sensor and compare its data with a analysis of updrafts/downdrafts from force balance equations. We are currently in the process of analyzing ALICE 6 data, however it appears that the vertical wind speed sensor performed flawlessly. The behavior of this balloon matched the prelaunch predictions fairly well with no fundamental change to the system other than the addition of a wind speed sensor.

Summary of ALICE Results and Future Flights. Reversible fluid altitude oscillations have been demonstrated for a terrestrial environment for a two balloon buoyancy system using helium gas and R114 reversible fluid. The performance of the balloon system has been modeled for day and night operations with higher accuracy for nighttime flights. A prototype vertical wind speed sensor has been flown and evaluated. A large number of systems issues have been studied in attempt to understand the behavior of this new class of planetary exploration system. Future flights will test advanced reversible fluid mixtures (such as X and Y) which have more favorable average molecular weights and thus higher potential buoyancy change capability for the same payload. Later flights will also test prototype navigation sensors for Mars and Venus application.

Planetary Aerobot Testbed

The Planetary Aerobot Testbed (PAT) was conceived to carry out proof-of-concept tests for the aerobot autonomous state estimation (ASE) and the autonomous control and navigation (ACN) subsystems previously described. It builds on the accomplishments the series of ALICE experiments conducted over the last two years that proved the concept of using reversible fluids to induce cyclical altitude variations about a stabilizing altitude. The testbed includes two principal subsystems: the aerobot vehicle itself and a workstation used for control and display, PAT will primarily address the challenges of aerobot missions to planets and satellites with solid surfaces ----- Venus, Mars, Titan In demonstrating the ASE functions, it will fly some sensors and emulate others It will use an advanced terrestrial reversible fluid system proven in the ALICE program

Planetary Aerobot Testbed Vehicle. The PAT vehicle (Figure 10) uses two attached balloons: helium in one provides most of the buoyancy, while a second, smaller balloon, provides altitude control by using a reversible fluid selected as described earlier for ALICE. Several reversible fluids are possible for use on Earth, each with a different condensation equilibrium altitude. A mixture of X and Y fluids, with a condensation altitude of about 10 km, depending on season, is a suitable fluid. With an appropriate amount of reversible fluid, the vehicle oscillates about the equilibrium altitude of the fluid. These oscillations are "forced" by the evaporation of the fluid at low altitude, which increases buoyancy and causes the balloon system to rise and by the condensation of the fluid at high altitude, which reduces buoyancy, allowing, gravity to pull the system down. For the helium/fluid system, the amplitude of this oscillation is expected to be about 4 or 5 km.

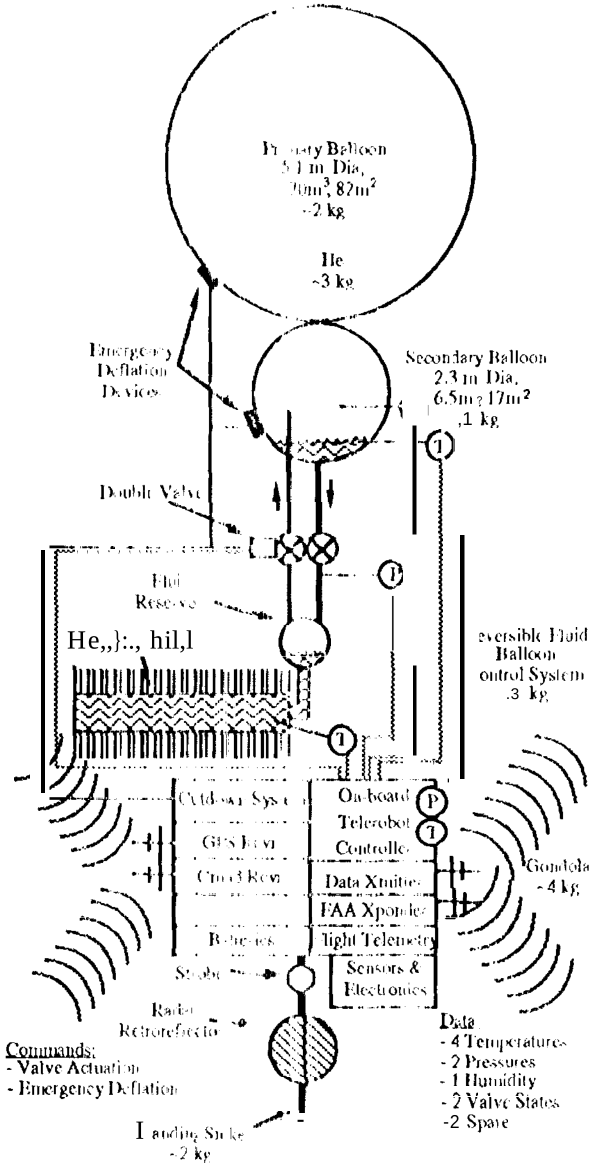

Figure 10. Planetary Aerobot Testbed Vehicle System

To descend, the liquid condensing in the cold upper half of the altitude cycle is trapped inside a small pressure vessel thus creating negative lift. The system then descends into warmer lower altitudes, and eventually settles on the surface. A landing "snake" keeps the gondola hovering off the surface. At any point in a descent, valves can be opened to allow the now super-heated liquid to boil and reinflate the small, buoyancy-controlled balloon. With a net positive lift, the system goes up to the cooler upper altitudes and resumes oscillation about the equilibrium altitude. It is this vertical control, combined with a varied and rich wind structure, that can enable long term, cyclic operations to and from landing sites on Earth.

The entire PAT vehicle mass is expected to be about 25 kg depending upon the degree of autonomy incorporated, efficiency of the heat exchanger system and the buoyancy control margin carried. The gondola system includes a remotely operated or autonomous controller> flight telemetry subsystem, Global Positioning System (GPS) receiver, geosynchronous satellite-c(J]] lrii~]t]l(ati(, rls subsystem, Federal Aviation Administration (FAA) transponder, redundant balloon cut-down subsystem controller, structure/insulation and batteries. The reversible-fluid heat exchanger system includes valves, actuators, heat exchanger fins, a reservoir, and plumbing,.

The PAT vehicle also has a navigation and sensory perception complement and an on-board controller/computer. PAT operates in two modes: telerobotic control in which commands from a workstation are used to operate the altitude control system and autonomous control in which these commands are issued by the vehicle computer based upon real-time sensory perception of the balloon thermodynamic state, ambient atmospheric conditions, and the desired actions, i, c., landing at a desired site.

Initially, many of the, ASE and ACN functions will actually be implemented in the PAT workstation. These functions will be migrated to the PAT vehicle as its computational capabilities are upgraded.

<u>PAT Workstation.</u> The PAT workstation will be able to display commands and vehicle status and will support the ASE and ACN functions at high rates. Complementary functions performed on the. aerobot vehicle will incorporate faster-than-real-time flight dynamics models of aerobot flight paths. The workstation will be used in the initial teleoperation phase to display the actual balloon trajectory and predicted trajectories based upon various control scenarios. Vertical profiles and views of planned balloon ground tracks will be generated.

Infrared Mongolfiere Aerobots

A research program is presently underway at JPL to evaluate the use of infrared Montgolfiere balloon technology for use in the outer gas planet atmospheres. There are three prime objectives to be accomplished during the course of this research:

<u>Thermal Modeling</u>. Detailed thermal models will be prepared to predict performance in the Jovian atmosphere. These models will be updated with data as received from the Galileo probe in December 1995, JPL has already been engaged in thermal modeling of balloons [3], and we have significantly advanced the state of the art with the highly successful ALICE balloon series. Modifications to modeling, will be necessary to account for a much lower molecular weight pressure, greatly increased gravity, and anticipated significant variations in thermal radiation levels.

<u>Balloon Materials</u> Balloon materials will be examined and tested in regard to selection of envelope material, infrared absorber coatings, and reflector coatings. Much work has already been accomplished by the French in the evaluation of material for a terrestrial IR Montgolfiere balloon. The thermal optical properties of transmittance, reflectance, and absorbance will be measured in the visible (solar) and infrared wavelengths for the most promising materials. This information is valuable for other potential uses of the materials, such as for the design of spacecraft insulation.

<u>Mechanisms</u>. Mechanisms will be examined and tested for deployment, initial fill, and altitude control. A helium balloon will lift an empty tethered IR balloon to height. The IR balloon will then be remotely disconnected, allowing it to descend and inflate through an open port in the bottom, similar to a parachute (Figure 10). The bottom of the balloon will be supported in an open position, as in recreational hot-air balloons, to allow for changes in pressure as the balloon ascends and descends. Hot gas will always be maintained in the *upper* part of the balloon. The most challenging part of the

mechanisms area is to design a system that will allow controlled ascents and descents. As previously discussed, among the systems to be studied are a hot gas venting system and an IR-variable liquid crystal film layer on the balloon.

(FIGURE 10)

Technology Development

Balloon Envelope Materials - (KTN/Andre)

Ask Jovan Mocanin for a draft of his paper. I'll abstract it for this section.

Thermal control

There are a number of areas of thermal control that will require development if a series of balloon aerobots are to successfully explore the bodies in this solar system which have atmospheres. In particular, the extremely harsh temperatures and pressures of the lower Venusian atmosphere will require the development of lightweight vacuum dewar technology that maintains its integrity at pressures up to 93 bars and temperatures up to 460° C.

The inner payload must be thermally isolated during operation, but yet must be supported during atmosphere entry, where forces may temporarily exceed the 500 level. When the aerobot rises back to cooler temperatures in the upper atmosphere, it must quickly reject its heat by means of a thermal switch, such as a gravity reflux heat pipe, which is a small hollow tube partially filled with a refrigerant fluid such as ammonia.

For aerobot flights in the atmosphere of Titan, extremely cold temperatures must be endured. Again, lightweight insulation techniques must be developed to allow the internal electronics to operate near room temperature, with minimum use of radioisotope heaters, while in an ambient temperature of about 75 to 95 K.

The Infrared Montgolfiere Aerobots (IRMAs) for the outer gas planets of Jupiter and Saturn are likely to operate near or somewhat below room temperature, while those of Uranus and Neptune may be required to operate in substantially colder ambient temperatures from about 60 K and higher

Power generation

One way to generate power during balloon ascents and descents is to use a wind-turbine type of power generator. An example of the potential power that can be generated by such a system has been calculated for real flight data attained in the ALICE flight series, as shown in Figure 4. For this very small 3kg balloon system, the change in buoyancy was only about +/- 3% during ascent and descent. The resulting velocities were approximately 1.3 m/sec. up and 0.7 m/sec. down. Power can be expressed as "force" times "velocity", and thus the amount of possible energy generated by this flight was "net buoyancy" times "balloon vertical velocity" This value has been calculated and is shown in Figure 6 for the condition of a continuous night flight with no balloon leakage. integration and averaging of this curve results in a total possible wind power (assuming 100% conversion) of 200 mw. Of course the added drag of a system to extract this energy will increase system drag and lower the velocity which will lower the total energy available.

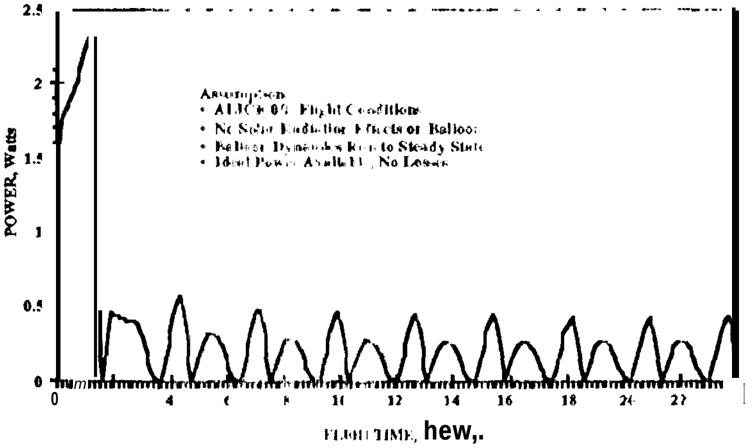

Fig. 6. Potential Power Available from ALICE Flight Profile

Conditions for a real flight at Venus would be more favorable than this terrestrial test flight. For a Venus aerobot, we assume a total mass of 30 kg and a variable buoyancy of +/- 25%, since we plan to use reversible fluids for Venus which have significantly low molecular weight (such as water). With an approximate average vertical velocity of 2.0 m/sec, this then converts to a total possible energy of 40 watts for Venus compared to 200 mw for the terrestrial analog.

Another place where wind turbine power generation can be applied is for outer planet aerobots. Developing techniques to change and control the buoyancy of IR Montgolfiere balloons a regular cycle of variable altitude can be sustained. This contained variation in altitude can drive a wind driven power generation system thus enabling very very long missions within the outer planet atmospheres without the need for radioisotope power sources.

Conclusions (KTN)

- **Near term opportunities**
  - **Venus Discovery (BEV-like missions)**
  - **BETA - Cassini connection**
  - **Mars 2001**

- **long range possibilities**
  - **VFR moderate class missions**
  - **Vertical mobility for Mars aerobots**
  - **O.P. IRM's replace atmospheric probes**
  - **Combined** Titan **aerobot with Saturn IRM Mission** with **dedicated orbiter.**

- **Summary**

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