

GUIDED MARS BALLOON PLATFORMS

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ABSTRACT

We outline a new Mars exploration concept for guided balloons that integrates balloon flight path guidance and autonomous navigation and control. These balloon platforms could observe Mars in collaboration with orbiters and surface rovers on global scales. We summarize the overall system concept, show how these balloons can be guided, and describe potential science mission scenarios illustrated with an example trajectory simulation using realistic systems and winds. We also discuss some of the system aspects of autonomous balloon platforms for Mars, in particular, entry, deployment and inflation (EDI).

1. INTRODUCTION

Balloons have been long recognized as unique, low-cost scientific platforms due to their relatively low cost and low power consumption. The successful Venera-Vega Project [1] demonstrated technical feasibility of deploying a balloon at another planet and performing scientific observations from it. Numerous concepts and technologies enabling planetary balloon exploration have been developed [2-7] in the last 15 years.

Guided Mars balloons are a new exploration concept that extends these past balloon ideas and augments and enables new measurements not possible from existing types of platforms. For example, orbiters are not *in situ* nor can they achieve the resolution of aerial vehicles. Landers do not move. Rovers, despite their recent unqualified success, have very limited range. Airplanes and gliders can remain aloft for only a few hours or minutes, respectively. Airship propulsion makes them very heavy and difficult to deploy at Mars. Finally, free balloons are totally at the mercy of the Martian winds. This innovative system concept, developed under support from the NASA Institute for Advanced Concepts (NIAC), enables long duration targeted planetary exploration on a global scale with *in situ* and remote observation capabilities [8].

The guided Mars balloon platform is highly adaptive and capable of observing planetary atmospheres and surfaces over long periods of time without consuming much power. The guided Mars balloon platform “orbits” the planet using the prevailing atmospheric winds as its trajectory is modified according to observational objectives. Studies of atmospheric dynamics, atmospheric chemical, and radiative processes on other

planets could become possible at an advanced level. Microprobes would be deployed over the target areas and perform a multitude of tasks at the surface or while descending, such as chemical, biological, meteorological, or thermal analyses, high-resolution imaging, measuring seismic activity, etc.

2. CONCEPT OVERVIEW

At the heart of this revolutionary concept for Mars exploration are long-duration planetary balloons with flight path guidance and control capabilities. A conceptual drawing of the guided Mars balloon platform is shown in Fig. 1. The drawing is for illustration purposes. The tether below the gondola is not to scale: the tether will be several km long. The figure shows a balloon in a shape of a 1:2 ellipsoid with a gondola and a deployed single-wing Balloon Guidance System (BGS) on a long tether below it. The single-wing BGS is a wing and a rudder attached to horizontal boom.

An ellipsoidal rather than a spherical balloon is employed for this example to improve performance of the BGS by reducing the aerodynamic drag on the balloon. We envision superpressure balloons that do not require carrying and dropping ballast to keep the balloon aloft. The ellipsoidal balloon in Fig. 1 reduces drag force by factor of two lower than for a spherical balloon of the same volume, and for an area and mass penalties of only about 10%.

The gondola, below the balloon houses scientific instruments, power, communication devices, etc. Below the gondola is the microprobe magazine that could hold a few to tens of miniature payloads. For this example system concept only 5 microprobes are shown.

The Balloon Guidance System (or BGS) is attached to the gondola via very strong, very long (3-8 km) tether. The BGS requires very little power (about 1 W on average) to operate, when it is not being reeled up to avoid terrain obstacles, and it can be made very light. This Mars BGS is expected to incorporate low-Reynolds number airfoil designs. The science payload could be split between the gondola and the BGS, e.g. the BGS in Fig. 1 illustrates cameras attached to it just below the large wing structure.

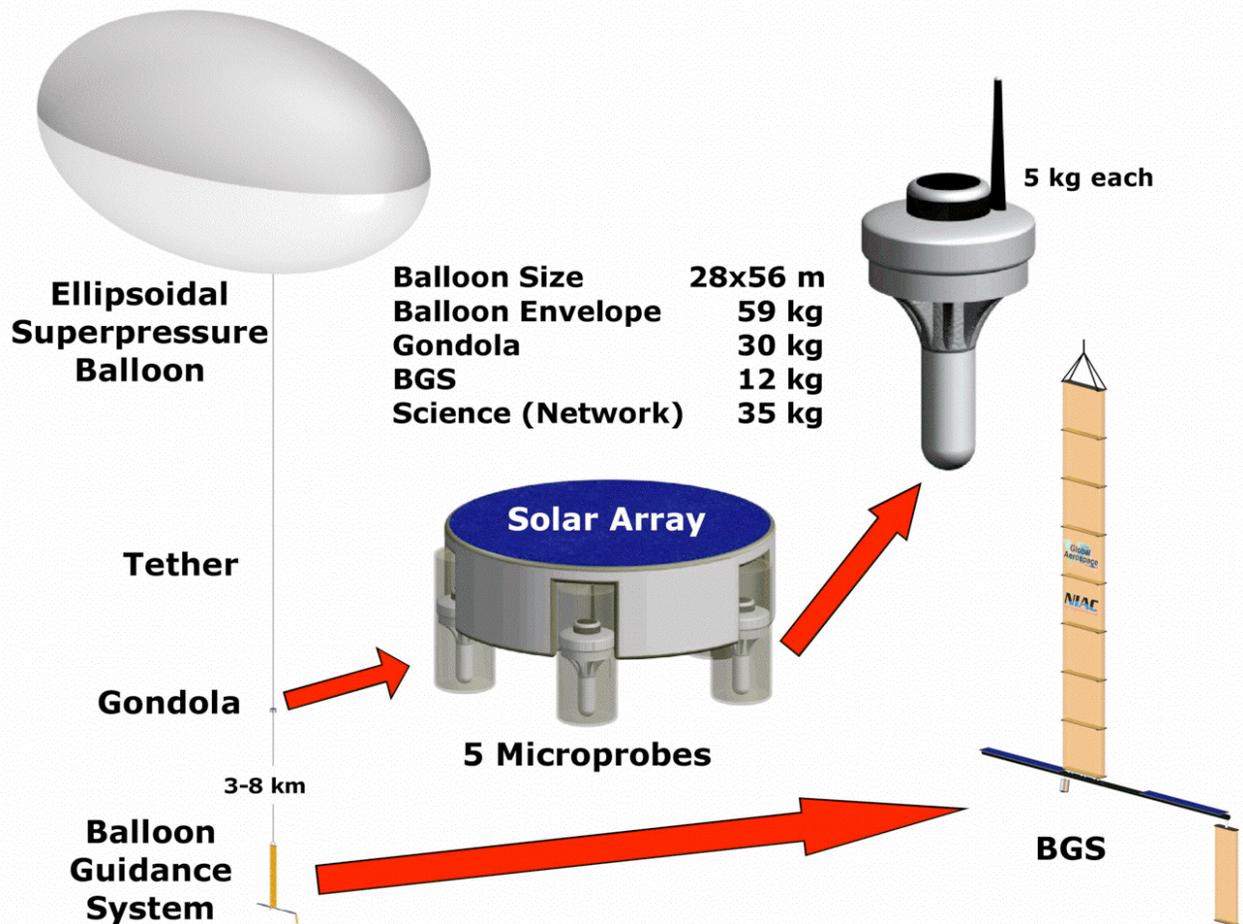


Fig. 1. Example guided Mars balloon system concept

3. BALLOON GUIDANCE SYSTEM (BGS)

In the past, the inability to control the path of Mars balloons has limited their usefulness, and therefore scientific interest in their use. Without flight path guidance technology, a Mars balloon has a high probability of impacting high topography and it cannot be commanded to observe a particular region of interest. The BGS vastly expands the capabilities of balloons for Mars exploration by providing the means to control their paths in the Martian atmosphere. In addition, a BGS reduces the risk of mission failure by avoiding regions with high topography.

A BGS exploits the natural wind field variation with altitude, generally observed on planets with atmospheres, to generate passive lateral control forces on a balloon using a tether-deployed aerodynamic surface below the balloon. A lifting device, such as a wing on end, is suspended on a tether well beneath the balloon to take advantage of this variation in wind velocity with altitude. The wing generates a horizontal lift force that can be

directed over a wide range of angles. This force, transmitted to the balloon by a tether, alters the balloon's path providing a bias velocity of a few meters per second to the balloon drift rate. A BGS enables a balloon to fly over surface targets for high-resolution reconnaissance or for deployment of microprobes, to steer around mountains to avoid collisions, to sample the atmosphere to map the abundance of trace gases that could lead to locating possible surface sources of these gases, and to explore a planet on regional and global scales. No longer are planetary balloons totally at the mercy of the winds.

Features of a BGS include the ability to:

- Passively exploit natural wind conditions
- Operate day and night
- Control balloon direction of balloon flight path in various wind conditions
- Be made of lightweight materials and inflatable structures
- Operate with very little power and without consumables

The difference in winds at different altitudes in the atmosphere creates a relative wind at the altitude of the wing (stronger winds are usually found at higher altitudes on Mars). An example of a wind profile at Mars is shown on Fig. 2 (from Mars-GRAM 2001 [9]). The BGS wing in the relative wind generates a lifting force that is directed sideways. The lifting force depends on the size of the wing, its aerodynamic properties, density of the atmosphere and strength of the relative wind.

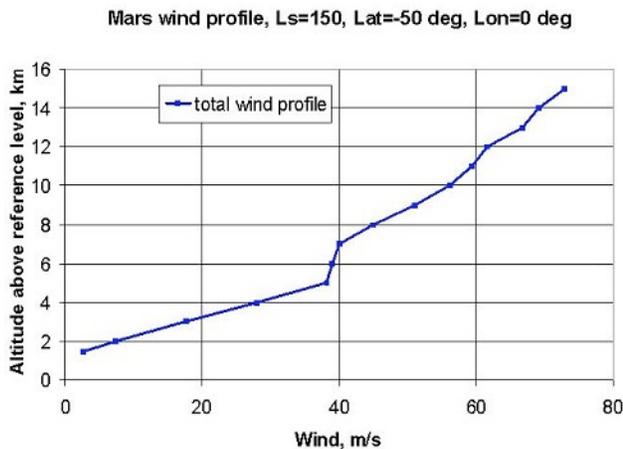


Fig. 2. Mars atmospheric wind profile.

The horizontal component of the total force produced by the wing can be used to change the path of a balloon in the winds. For this example wind profile the wind at 10 km altitude, where the balloon would be floating, is about 56 m/s while the wind at 3 km, where the BGS would be situated, is about 18 m/s. The resultant relative wind is therefore 38 m/s. This level of relative wind could apply a cross-wind delta-V to the balloon of the order of 4 m/s for an 8 m² wing operating with a lift coefficient of 0.8.

The aerodynamic surface of a Mars BGS will be operating at low Reynolds numbers (~1000). For these low Reynolds numbers, drag coefficients are significantly higher and maximum lift coefficients are a little lower than for airfoils at higher Reynolds number operation. The reduced Lift-to-Drag ratio is quite a challenge for systems, which must generate their lift aerodynamically while providing power to overcome the drag. However, for the BGS, the weight is supported by buoyancy. The “lift” from the wing is directed close to horizontal and predominantly across the flight path of the balloon. The drag acts mostly to slow the balloon down, and is relatively unimportant to the operation of the system.

The performance of the generic BGS technology has been demonstrated in scale model tests at Earth where

the stability, dynamics and aerodynamic performance has been verified for Earth-based systems [10].

4. EXPLORATION CAPABILITIES

At Mars, guided balloons could float close to the surface (6-12 km, depending on location and season) and could provide a wealth of new and unique observations. Some observations, such as the magnetic anomalies on Mars, are, quite possibly, only feasible from a suborbital platform. They could provide spatial coverage comparable to that of satellites, but they additionally enable opportunities for *in situ* atmospheric and surface analysis with deployable science packages and high-resolution surface imaging.

The extended range and long flight duration (~700 days) of guided Mars balloons could provide opportunities for highly adaptive observations during science missions. Just like rovers, if an interesting target is found, a balloon can be commanded to reposition itself to observe it. In this case, the range is the entire planet, not the immediate vicinity of a landing site. A platform can deploy small rovers, miniature geo-chemical laboratories, or it can distribute small surface and atmospheric sampling probes over Mars at particular sites of interest.

Small thermal-emission spectrometers and high-resolution cameras onboard these platforms could image the surface and map mineralogical abundances at the spatial scales of centimeters on the global scale. Magnetic field measurements from altitudes of just 3 to 12 km will provide an unprecedented opportunity to study Martian geology and geophysics, and evolution of the planet. With these platforms, we can visit Polar Regions to closely observe sublimation of polar caps during the spring and the genesis of local dust storms, and then migrate towards tropical regions to observe the formation of dust devils or trace the plumes of atmospheric water vapor. We could release ice penetrators over the polar cap to study the layering in the ice sheets, miniature weather and seismological stations, small rovers and crawlers while flying over highlands and lowlands, and subsurface penetrators over the areas where shallow subsurface ice could be present.

A guided Mars balloon can participate in the reconnaissance of the landing sites rich in usable resources (such as water ice) for robotic or human base. Small navigational beacons and atmospheric sensors could be deployed over potential landing sites to mark and monitor landing zones for incoming piloted spaceships.

Potential science mission applications, described below, include search for the origin of atmospheric methane,

crustal magnetic anomalies mapping, precise emplacement of surface networks, polar night studies, and efficient sample return assist.

4.1 Mission to Search for Origin of Methane

One objective of a guided balloon mission could be to determine the nature of the source of the methane in the atmosphere of Mars [11] – is the source biologic or not? – and to locate the source of methane emission. To distinguish between biologically and abiologically produced methane, instruments onboard of the platform would measure isotopic fractionation of the methane isotopes in the atmosphere of Mars using a Tunable Laser Spectrometer (TLS). The measurement would look at the isotopic ratio of carbon in the methane (C^{12}/C^{13}) and isotopic ratios in other trace gases (water vapor and others). This measurement can provide clues to the presence of life at Mars. Methane-making organisms discriminate between isotopes as they feed on a global reservoir of CO_2 . These organisms are consuming the lighter isotope of CO_2 , $C^{12}O_2$, while the heavier isotope, $C^{13}O_2$, is avoided. If the ratio of C^{12}/C^{13} in methane were different from that in CO_2 , it would offer strong evidence for a biological source.

The TLS instruments could be housed in the gondola of the platform. Several instruments may be needed as isotopes of the other atmospheric constituents may need to be measured. Guided balloon platforms could also carry a magnetometer for simultaneous measurements of the magnetic field anomalies. Crustal magnetic anomalies at Mars may be indicative of preservation of subsurface structures that harbor methane-producing biota or outgas methane into the atmosphere.

The platform could float over the southern highlands performing isotopic and magnetic field measurements. The preferred seasons for the observations is late southern spring ($L_s=200^\circ-250^\circ$) or late southern summer ($L_s=330^\circ-360^\circ$), to avoid the season of major dust storms. The platform could circumnavigate Mars several times at different latitudes, mapping isotopic ratios and methane concentrations. This would enable establishing gradients of methane concentrations in the atmosphere and to locate the source of methane on the surface.

4.2 Mission to Characterize Crustal Magnetic Anomalies

Mars Global Surveyor (MGS) discovered strong magnetic anomalies in the Southern Hemisphere during its aerobraking phase [12]. However, crustal magnetic field anomalies measurements from orbital altitudes lack resolution needed to resolve the question of origin of the anomalies. In addition, weak crustal magnetic field anomalies are obscured by the solar wind.

The plot in Fig. 3 shows Southern Hemisphere map of the crustal magnetic anomalies from MGS. There are no anomalies in the Northern Hemisphere, which may have implications for the origin of the anomalies. To study the anomalies high resolution and higher sensitivity observations are needed.

A mission objective for characterizing these magnetic anomalies could be to study the history of the Mars internal magnetic field and the crustal accretion process, and the detection of subsurface water reservoirs. One or two vector magnetometers and attitude sensors could be positioned at the gondola and/or along the tether. Simultaneous high-resolution visible and infrared imaging of the surface could be performed to link the measurements of the magnetic field and subsurface water to topographic features.

The balloon platform could complete several “orbits” over southern highlands, producing multiple traverses of the anomalies. As a result, the measurements would enable characterization of the spatial frequency of the magnetic anomaly pattern, the depth, thickness and lateral extent of the sources. The relations of the magnetic features to topography would be established and the subsurface water reservoirs will be mapped.

Guided balloon platform equipped with an array of magnetometers can enable high resolution observations by being much closer to the surface and can have higher sensitivity than orbital measurements by using magnetic field gradient measurements.

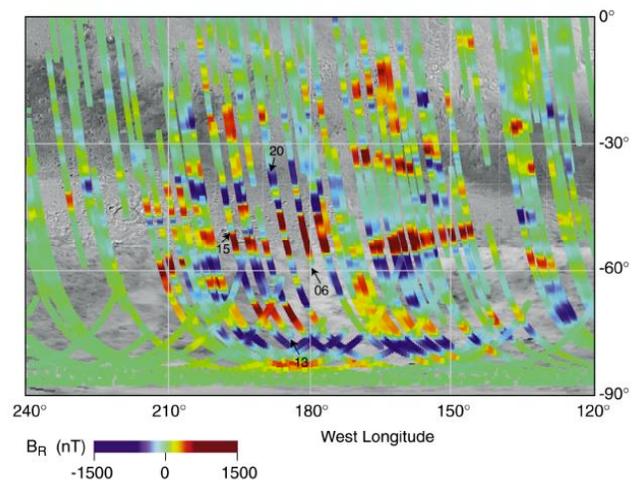


Fig. 3. Map of crustal magnetic anomalies on Mars (NASA GSFC)

4.3 Mission to Emplace a Surface Network

Guided balloons could carry many lightweight microprobes that would be dropped to the surface over

target areas. Unlike microprobes entering the atmosphere from space, these would not require an atmospheric entry heat shield for each probe. Emplacement from a guided balloon avoids several constraints on landing site latitude inherent to deployment of lander from direct entry. Also there are fewer limitations on elevation of landing site since one does not need thick atmosphere above the site for deceleration of a probe. Guided balloon microprobes can be targeted much more precisely than when deployed from orbit since entry uncertainties are no longer in play. Finally, the microprobes could be placed in different Martian regions; polar, floor of large depression (Hellas basin), “narrow” canyon (Valles Marineris), highlands, lowlands; in order to give a full global picture of the atmospheric changes, or to enable seismological sounding of the planets interior from a global network.

One objective of the Surface Network Emplacement mission could be the establishment a network of 4 combined seismological and meteorological stations (a SeisMet Network) on the surface of Mars. A guided balloon could carry up to 5 microprobes that could weigh 5 kg each and be capable of operating for 1 year on the surface. Mars microprobes, including a meteorological and seismometer mini-lab, would rely on Deep Space 2 (DS-2) [13] and NetLander [14] technology heritage. Surface penetration speeds could be as low as 40-60 m/s (1 m² decelerator, 5 kg probe from 10 km). Each microprobe could carry a seismometer, a simple soil analyzer and meteorological sensors (pressure, temperature, humidity and winds). A mission profile could consist of the balloon flying to pre-selected sites and deploying the microprobes and then continuing with an imaging mission afterwards. Preferred positions for the surface stations are at the nodes of a tetrahedron. This mission would produce a map of the internal structure of Mars and validate atmospheric circulation models.

Fig. 4 displays one 60-sol simulation of a guided balloon deploying a SeisMet Network. The trajectory is plotted over a filled contour plot of surface topography. The contours are plotted with 1 km interval. The color scale of the height contours is shown on the legend in the figure. The simulated trajectory is shown by the black curve, sites of the surface stations are shown by red triangles and a square. The highest locations on the map are the Tharsis rise and Olympus Mons (latitudes from -30° to 20°, longitudes from -140°E to -90°E). The lowest location on the map is the Hellas Basin (centered on -40° latitude and 70°E longitude).

The simulation starts on July 13, 2013 at the latitude of 50° and longitude of 55°. The date corresponds to the arrival date for the lowest energy Earth-Mars Type I trajectory of the 2013 opportunity. The season is almost equinox (Ls=356°). The geographic location for the start

of the trajectory is consistent with potential entry location for the 2013 opportunity. Wind data for the simulation is supplied by Mars-GRAM 2001[9].

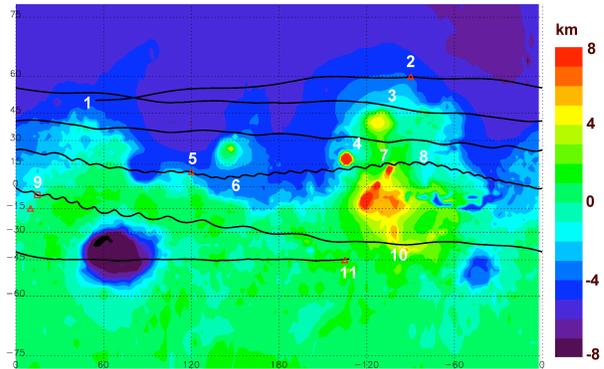


Fig. 4. Simulated guided balloon trajectory.

As discussed earlier, these microprobes can be deployed with great targeting precision, an important goal for future small landers. Fig. 5 shows a map of a portion of the Martian canyon with a narrow band of the olivine outcrop on the bottom (shown in purple). The yellow ellipse shows the landing error ellipse for a direct-entry probe landing from approach to the planet (the ellipse’s dimensions are approximately 120 by 20 km, typical of the failed DS-2 probe landing accuracy). This example shows that interesting geology on Mars, with spatial dimensions on the order of a kilometer, would be very hard to target with conventional, direct-entry probes. Guided balloons, on the other hand, can target geologic features with deployable science packages with greater precision.

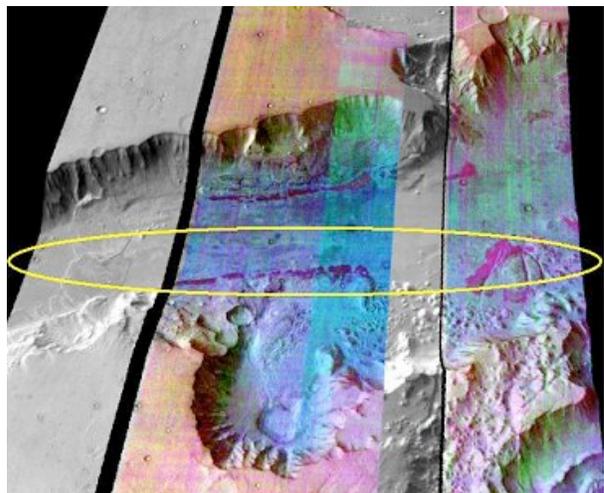


Fig. 5. Olivine outcrop and landing ellipse for existing space probes, like DS-2 (NASA/JPL/ASU)

4.4 Mission to Explore the Polar Night

An objective of a mission to explore the polar night could be to study polar winter processes – such as CO₂ accumulation, formation of clouds, etc. A guided balloon platform could carry a thermal spectrometer to measure atmospheric and surface temperatures and deployable microprobes to sample and analyze the underlying terrain. These balloons, flying in the dark for days on end, would need to rely on non-solar photovoltaic power sources, which may need to include radioisotope or wind power approaches. A mission of this type could produce observations to validate CO₂ cycle models and provide insights into formation of the polar terrains.

4.5 Mission to Support Mars Sample Return

Guided balloons could provide logistical support to Mars Sample Return missions. One objective of such a support mission could be to perform site surveillance to assist orbiters in site selection. Another, more direct, objective could be to enable sample return from multiple sites on a single return vehicle. This objective would utilize the cooperative capabilities offered by the guided balloons and sample acquisition rovers. In this mission profile, illustrated by Fig. 6, multiple rovers could collect samples at different sites across Mars. The rovers are able to search local terrain and to select samples for return to Earth. The samples are packaged into a container and transferred to a guided balloon that could overfly the sample collection sites. The actual transfer mechanism may involve a long, lightweight tether that is being snatched from the air by the guided balloon's BGS, as illustrated in Fig. 6, or many other approaches. After sample collection by the guided balloon, it overflies the site of the sample return vehicle and drops the sample canister for collection by a rover. The rover then transfers the canister to the Sample Return Vehicle that will take the samples to Earth. The sequence repeats until several samples from different sites on the planet are placed onto the sample return vehicle. The sample return vehicle then takes off and returns the samples to Earth. This mission would enable return of samples from several distinct sites on a single return vehicle, maximizing mission scientific return. In this way several samples from widely separated sites on Mars can be delivered to Earth on a single return vehicle.

5. GUIDED BALLOON PLATFORM SYSTEMS

Here we discuss one example platform design based on near-term technology (i.e. 3-10 year technology horizon) and the mission scenario to emplace a surface network. A Mars guided balloon platform consists of a superpressure balloon envelope; a gondola; a BGS; science instrumentation; and entry, descent and inflation (EDI) hardware. Since we have already discussed the

BGS, a key element to the capability, we will focus this discussion on the balloon, gondola, EDI, and the overall flight system.

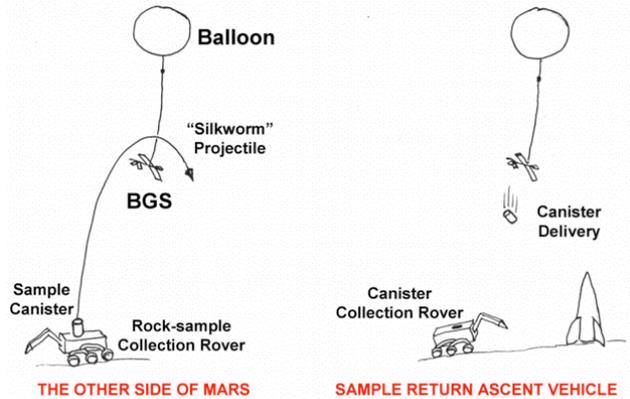


Fig. 6. Mars Sample Return Mission support

5.1 Balloon System

The balloon system is made up of the envelope and top and bottom fittings. One promising option for balloon envelope material is a composite material consisting of 1-micron Mylar, a 38-Denier PBO thread and a 3-micron PE film. The surface density of this material is estimated at 0.012 kg/m². A similar, but thicker, material was proposed in a previous Mars balloon study [5]. The need for a composite material arises from the fact that it is impossible to find all the needed mechanical properties in a single material. Hence, in this proposed composite material Mylar provides substrate stiffness, Polyethylene provides fracture toughness and pinhole resistance, while the scrim provides high-strength at low surface mass.

The shape of the envelope could be spherical, or ellipsoidal. The shape of the balloon has implications on material strength requirements, since it is superpressurized, and on the aerodynamic drag it creates as it is pulled around in the air by the BGS. One attractive shape is ellipsoidal with the long axis in the direction of the balloon's relative wind in order to minimize aerodynamic drag.

5.2 Gondola

A gondola is suspended below the balloon and contains science instrumentation, communications gear, power subsystems (solar array and batteries), thermal protection equipment, attitude knowledge sensors, the BGS winch hardware, central computer control, and mechanical structure and mechanisms. Fig. 1 displays an example computer drawing of the gondola for a network emplacement mission.

5.3 Entry, Deployment and Inflation

Entry, deployment and inflation (EDI) is the sequence of events by which the entry probe decelerates in the atmosphere and the balloon system is deployed and inflated. Fig. 7 illustrates one concept for a sequence of events that take place during EDI.

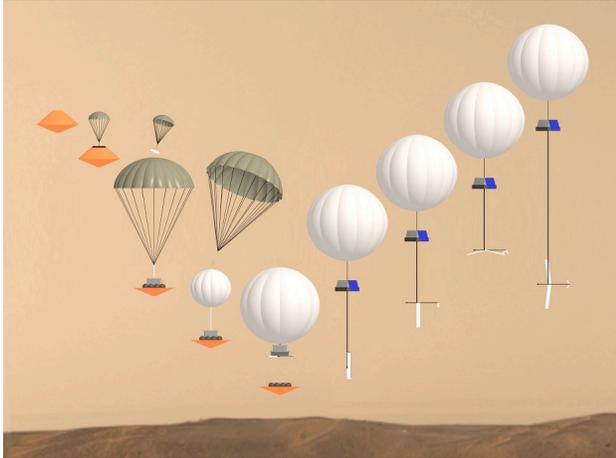


Fig. 7. An example EDI sequence

Fig. 8 shows one example for the packaging of the entry vehicle. The aft (top) part of the entry vehicle is occupied by the parachutes and a canister that houses the balloon envelope. The gondola is shown below the balloon envelope canister and above a folded BGS wing (inflated, rigidized versions are also possible). In this version, the wing separates from the gondola and unfolds, while being lowered on a winch upon ascent to the floating altitude during the EDI.

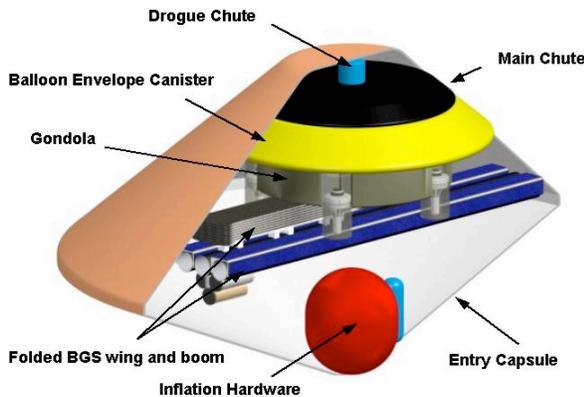


Fig. 8. Guided Mars balloon entry probe

Below the folded BGS is a cryogenic, hydrogen balloon inflation subsystem. The gondola houses the circular solar panel at the top, five deployable surface stations positioned on the circumference of the gondola, the

winch and stored tether of the BGS. The folded envelope and supporting structure of the inflatable BGS wing and the folded boom of the BGS are attached to the bottom of the gondola.

The entry and descent phases (see Fig. 7) would be very similar to previous Mars lander missions. A blunt conical heat shield reduces the enormous interplanetary velocity and absorbs the heat generated by passing through the atmosphere. The aft cover is released and a supersonic parachute is deployed at a Mach number of ~ 2 . This slows the descent rate significantly into the low subsonic range to the point the internal components no longer need protection from the ram air and the heat shield can be dropped. As the system approaches terminal velocity on the parachute, the inflation phase commences. The gondola and attached equipment are lowered, and the weight is used to stretch out the balloon envelope vertically. A load member inside the balloon could absorb the shock generated during deployment as the envelope goes taut. The inflation equipment is mounted below the balloon, and will be jettisoned when the inflation of the balloon is complete. An inflation tube is used to carry the gas up to the initial inflation bubble towards the upper end of the balloon and could also support the deployment shock. Once the balloon has reached a size comparable to the parachute, the parachute will be cut away. Upon completion of inflation, the inflation hardware will be released, and the system will ascend towards an equilibrium float altitude, at which point the BGS can be deployed. Mars balloon EDI technology is currently being studied by NASA.

The cryogenic inflation hardware (the tanks holding the buoyant gas, valves and pipes) can have a substantial mass. For this reason, we assumed the use of hydrogen instead of helium as a buoyant gas and stored in a cryogenically cooled container. Warming up cold hydrogen for inflation requires additional equipment, however the estimated savings in mass are still substantial – we estimate the mass of cryogenic inflation hardware for 8.3 kg of hydrogen at about 16 kg. Table 1 summarizes the entry vehicle mass breakdown.

Table 1. Entry vehicle mass summary

Component	Mass, kg
Main parachute	25
Heat shield	62
Back shell	67
Inflation hardware	16
Balloon flight system	140
Contingency (9%)	30
Total	340

5.4 Flight System Summary

The flight system mass was estimated including appropriate contingency for so early in the development process. Table 2 summarizes the mass and power budget for this example flight system design.

Table 2. Flight system mass budget

BGS & Balloon		71
BGS and Winch	12	
Buoyant Gas	9	
Envelope	50	
Gondola		30
Structure	15	
Communications	5	
Power	5	
Thermal	5	
Science Payload		35
Microprobes (5)	25	
Camera Systems	9	
Magnetometer	1	
TOTAL		136
Allowable Mass		140

6. SUMMARY

A concept for planetary exploration is described in the context of Mars exploration. The key elements of the concept are: long-duration-flight autonomous balloons, balloon flight path guidance, lightweight power generation and storage, and multiple, deployable microprobes for atmosphere and surface exploration. A relatively small and light balloon guidance system would enable repositioning the platform on a global scale for *in situ* analysis and targeted deployment of atmospheric and surface microprobes. Deployment of microprobes from balloons eliminates atmospheric entry and deceleration hardware thus reducing overall mass and permitting more science payload or more microprobes. This concept could enable low-cost, low-energy, long-term global exploration of the atmosphere and surface of Mars and other planets.

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