JBIS, Vol. 61, pp.2-13, 2008

A REVIEW OF BALLOON CONCEPTS FOR TITAN

RALPH D. LORENZ
Johns Hopkins University Applied Physics Lab, 11100 Johns Hopkins Road, Laurel, MD 20723, USA.
Email: Ralph.lorenz@jhuapl.edu

Concepts for lighter-than-air exploration of Titan are reviewed. Logical vehicle designs with existing power sources (primary batteries, or 100 We-class radioisotope power supplies) are strongly bifurcated into small (few kg) vehicles with lifetimes of only a few hours/days, or larger (100 kg+) vehicles with lifetime of months to years. A wide range of the latter class of vehicle exists, including buoyant-gas and hot-air (Montgolfière) concepts, with and without altitude control or propulsion. An attractive intermediate (10s of kg, but long-lived) class of buoyant gas balloon would be enabled by small (0.5-10 We) radioisotope power supplies, not presently available in the USA. The marginal feasibility of high altitude solar-powered balloons is discussed.

Keywords: Titan, balloon, radioisotope power

1. INTRODUCTION AND HISTORICAL BACKGROUND

Titan is a unique place in the solar system. Not only is it a world with a dynamic atmosphere and a diverse landscape [1, 2, 3], but its low-gravity, thick-atmosphere environment lends itself to exploration by atmospheric flight. Motivated by prospects on both sides of the Atlantic for future exploration of Titan, specifically NASA's Outer Planets Flagship studies and ESA's Cosmic Visions studies, we review here some key factors and design options for balloon flight specifically.

Ballooning is a centuries-old activity on Earth (e.g. see Table 1), and the idea of ballooning on Titan is not new – the first discussions of balloon concepts appear some 30 years ago – a sketch of a rather impractical hot air balloon burning atmospheric methane in a supply of oxidant brought from earth appears in a 1976 Martin Marietta study [4] and more serious discussion of solar Montgolfière concepts was introduced by Blamont in 1978 [5]. More refined thinking followed the Voyager 1 encounter in 1980, which resolved some key uncertainties regarding the pressure and temperature conditions in the atmosphere: helium balloon and airship concepts were explored in prescient detail by Friedlander [6, 7]. Visions of Titan ballooning suffered a hiatus in the late 1980s and early 1990s as the mission that became Cassini-Huygens was formulated and then moved into implementation, although at least one small study (BETA – Balloon Experiment at Titan [8]) was conducted, and of course the in the meantime the first actual planetary balloons (the Soviet-French VEGA balloons) flew at Venus in 1984 [9, 10]. A previous paper [11] reviews 20th century Titan exploration concepts, including aeroplanes and helicopters.

In the present decade, with Cassini on its way and with attention shifting to the future, several studies have been per-

Part of this work was presented at the 5th International Planetary Probe Workshop held in Bordeaux, France, June 2007. (http://www.rssd.esa.int/SM/IPPW/).

TABLE 1: *Milestones in Ballooning*.

3rd Century	Hot air balloons as toys in China
1767	Joseph Black in Scotland suggests hydrogen-filled bags should rise in air.
1783	(March) Montgolfier brothers build paper balloon – hot air flight
1783	(December) Charles flies hydrogen balloon
1860s	Both sides use (gas) balloons for observation in American Civil War
1929	Circumnavigation of the world by airship Graf Zeppelin
1950s	Genetrix/Moby Dick spy balloons. Project ManHigh
1960	Modern Hot air balloon developed by Ed Yost
1978	Montgolfière balloons proposed for Titan by Jacques Blamont
1982	SAIC/Friedlander study of balloon/airship concepts for Titan
1984	Soviet Helium balloons fly around Venus, tracked by VLBI
1991	Virgin Pacific Flyer hot air balloon flight Japan – Canada
1997	Balloon Experiment at Titan (BETA) study
1999	Breitling Orbiter 3 (a Roziere) Circumnavigates world in ~20 days
2003-2006	GSFC TOAM, Langley, JPL Visions Mission, JPL TiPEX
2018	Flagship Launch?
2028	Flagship arrival – Montgolfière Deployment at Titan?

formed. These have typically invoked at most a few $\$10^5$ of effort and have invoked reasonable, but usually ad-hoc, scientific objectives focusing in particular on goals that were anticipated pre-Cassini to remain of interest but unfulfilled by Cassini [12], specifically high-resolution imaging of various parts of the surface, and acquisition and analysis of samples of surface material. Lacking constraints associated with a specific mission opportunity (e.g. launch vehicle, cost cap, etc.) these studies often embraced a variety of appealing but technologically demanding mission architectures, with an airship being found to be a particularly attractive since it offers directed sampling ('go-to') capability. Airship concepts were explored in two separate NASA 'Visions Mission' studies, by JPL and NASA Langley groups respectively [13, 14]. Later thinking moved towards hot-air balloons (e.g. Fig. 1), with two separate ad-hoc concepts TOAM (Titan Aerover Orbiter Mission) by NASA-GSFC [15] and TiPEx (Titan Planetary Explorer) by JPL [16]. In the meantime some important technology development has been undertaken, principally at JPL in relation to airships [17] but more generally applicable [18] – these developments include flight guidance and autonomy [19], materials development and testing [20], autonomous pointing of a communications dish from an airship [17], and deployment and inflation of an airship during parachute descent [21].

Several other developments are worth noting. The great success of the Mars Exploration Rovers in 2004 and since has underscored the public appeal of in-situ exploration by mobile platforms, and the early 21st century has seen a dramatic proliferation of robotic systems on Earth, from Unmanned Aerial Vehicles (UAVs) such as the missile-toting Predator to Roomba carpet-cleaning robots. Thus the notion of autonomous mobile systems (the Titan-Earth one-way light time of over 1 hour makes teleoperation impossible) is becoming perceived as a more practicable matter than it once was. The tremendous impact of the use of aerocapture (easier at Titan than at any other planetary body) in efficiently delivering large payloads into Titan orbit [22] has also been noted, making it realistic to contemplate mission architectures wherein an in-situ platform like a balloon could be supported by a very capable orbiter. This has two implications, first that an orbiter can directly augment a balloon science return by acting as a data relay and (less importantly) by providing navigation support. Second, some wide-area survey science objectives - although not perhaps the highest-resolution surface imaging - can be met by an orbiter, allowing the balloon to be focused on the in-situ goals for which it is uniquely suited. (Note that unlike at Mars where a large-aperture camera in a low orbit such as HiRISE on the Mars Reconnaissance Orbiter can attain sub-m resolution, Titan's thick hazy atmosphere degrades short-wavelength imaging, and forces a long-duration orbiter to a high altitude, >1000 km, such that attaining resolution of better than a few tens of meters will be extremely difficult.)

It was initially assumed that a balloon on Titan without active propulsion would simply drift due Eastwards in Titan's zonal winds, hence the early attention to propelled airships, although the prospect of sailing (exploiting a vertical gradient in wind speed with a 'wing' suspended on a tether) has been suggested [23]. However, as knowledge of Titan's topography and variable winds grows, it has been realized that some traverse in latitude is likely. Furthermore, the near-surface winds may be dominated by a component due to the gravitational tide of Saturn on the atmosphere, in which case the wind variations may be predictable [24], and as with recreational ballooning on Earth, exploitable.

Fig. 1 Concept for a Titan Montgolfière. (Artists impression by Tibor Balint)

In the ballooning field on Earth (see also Table 1) several developments are worth noting. Record-breaking transoceanic and round the world flights have garnered some public attention, and stimulated a number of technological balloon developments [25, 26].

The availability of modern microcontrollers and lightweight digital cameras makes it possible for amateurs and students to conduct small-scale but significant stratospheric ('Near-Space' or 'Balloonsat') balloon experiments [27, 28], providing many outreach opportunities and engaging a potentially wide community in activities analogous to those that might be conducted at Titan. More elaborate versions of similar electronic systems have been flown in the marine troposophere in Lagrangian meteorology experiments [29]. These tetrahedral balloons ('tetroons') were equipped with satellite telephone modems allowing altitude changes via buoyancy control to be commanded remotely on flights across thousands of miles of ocean. There has additionally been progress [30] in the application of propelled near-spherical balloons such as the "White Diamond" [31] for low-altitude wildlife filming in the canopy of the Guyana rainforest. This type of vehicle, able to conduct (albeit with an on-board human pilot) precision near-surface manoeuvring and sampling, is of a similar mass to what might be contemplated for more advanced Titan surface exploration. These various developments set the stage for visualizing Titan ballooning as a feasible enterprise.

2. PROGRAMMATIC SITUATION IN 2007

Between January and August 2007, a major NASA study (~$1M effort, led at the Applied Physics Laboratory with JPL and Langley participation) considered options for future Titan exploration. This study differed in several respects from the smaller ad-hoc concepts studies. First, this 'Titan Explorer' mission [32, 33] responded to a NASA Headquarters-determined Flagship 'opportunity' with stated launch vehicle options in the 2015-2022 timeframe (i.e. only 8-15 years from study start), and specified planetary protection requirements, Deep Space Network communications support and radioisotope power supply options. The ~$3B budget target for the mission included the cost of any required technology developments: this factor together with the schedule encouraged a pragmatic attitude toward technical complexity. Second, the study was the first in which a

12-member community-representative Science Definition Team (SDT) was designated by NASA Headquarters from volunteer scientific experts in outer solar system science (in academia and agencies). This SDT determined a broad set of scientific objectives that were best addressed by a multi-element architecture, comprising a Titan orbiter, a lander and a balloon. The orbiter would make global radar and infrared maps, study the atmosphere and its seasonal changes with optical and near-infrared imaging, ultraviolet, thermal infrared and microwave spectroscopy, and direct sampling; it would also measure energetic particles, gravity and magnetic fields. The lander would made a detailed chemical analysis of surface material, and make long-term meteorological and seismological measurements, while the balloon would perform a long traverse with high resolution imaging, subsurface radar sounding, and in-situ meteorology. The orbiter mission duration would be 4 years, and that of the lander and balloon was specified at 1 year (although no obvious factors limiting the life to that value were identified.)

The balloon was preferred over alternative means of attaining large-scale mobility at Titan (such as airships, or heavier-than-air platforms such as airplanes or helicopters [11]) for several reasons. First, the lift performance of thermally-driven buoyancy is very good (see later) in Titan's thick, cold atmosphere compared with buoyant gas like helium or hydrogen when the tankage mass is taken into account. Further, a Montgolfière or hot-air balloon is much more robust to small leaks or tears in the balloon envelope than a buoyant gas balloon, assuring attainment of the desired lifetime. Second, despite the thick atmosphere and low gravity, heavier-than-air vehicles on Titan require extremely low wing loading to achieve low enough power requirements for flight (a radioisotope power source RPS may supply ~100 W of electrical power (100 We) for a mass of 20-40 kg) making them necessarily resemble sailplanes or human-powered aircraft like the Gossamer Albatross. Such low wing loading raises deployment and robustness challenges, as noted elsewhere [34, 35].

Although designs were not pursued in detail, it was recognized [32] that the existence of the in-situ platforms (lander and balloon) might allow the deployment of small sub-vehicles of a variety of types to enhance the science return. These could include profiling drop-zondes released from the balloon, or a 'mole' like that carried on the Beagle 2 lander to Mars released from the lander, or a small battery-powered UAV launched from the lander to image the lander and its surrounds. (While long-duration flight powered by radioisotope generators on Titan requires low wing loading and thus creative structural design, higher-power but short duration [1-5 hours] battery flight is relatively trivial - this concept is discussed elsewhere [36].)

A variety of balloon concepts were sketched out (see Table 2) and their technological development requirements, robustness and capability to address science objectives were considered. The diversity of Titan's landscape is such that as long as a platform can traverse a large distance, it is likely to encounter a range of interesting terrain: directed mobility was not felt to offer a science gain commensurate with the technical complexity and risk associated with that capability. Thus a free-floating Montgolfière was chosen as the aerial platform. Such a platform at an altitude up to 10 km would likely, given the winds measured by the Huygens probe (Fig. 2), make one to two circumnavigations of Titan during a nominal lifetime of 1 year.

In the Titan Explorer concept [32], the orbiter, lander and balloon are carried to Titan together on a single cruise stage launched on an Atlas 551, but enter Titan's atmosphere in separate entry vehicles (with the orbiter in its aerocapture aeroshell re-emerging some minutes later!). This modular approach allows the mission to be adapted to fiscal constraints and to partnering opportunities, by the elimination of balloon or lander, or the substitution of smaller elements for either or both of them.

Entirely separately from the NASA study, ESA solicited mission concepts in mid-2007 for further study as options for Medium- and Large-class (~400 Meuro and ~650 Meuro) missions in the Cosmic Visions programme, for possible implementation in the 2015-2025 timeframe. One of the missions selected for further study (note that the ad-hoc proposals in response to this solicitation, which have not been published, were not the result of funded engineering study, and thus presently have a considerably lower technical maturity than the NASA Flagship study) is TANDEM (PI Athena Coustenis, Observatoire de Paris-Meudon), a concept for the exploration of Titan and Enceladus, including elements such as penetrators, small landers and a Titan balloon.

In coming months and years, NASA and ESA may decide to pursue a Titan mission. The present paper outlines balloon possibilities for Titan, including concepts that were not within the scope in the NASA Flagship study, since within an international framework a range of other options may be contemplated. Emphasis is given to the heat and electrical energy requirements as well as the different buoyancy options. We also discuss briefly some other aspects of Titan ballooning such as materials and longevity.

3. TITAN ENVIRONMENT AND DESIGN SPACE

It is important to recognize that the near-surface Titan environment, while facilitating mobility, is challenging from a longevity standpoint. The lack of solar power (insolation at the surface is ~1/1000 of that at Earth) precludes that as a power source, and the thick, cold atmosphere (94K, 5.3 kgm^{-3} air density, some 4x that of Earth's atmosphere at sea-level) means active heating is required for operations sustained over any period more than a few hours. Profiles of the Titan temperature and density are given in Figs. 3 and 4.

It will be recalled that the 1.3 m diameter Huygens probe, even though it had a 5 cm thick layer of foam insulation, lost some 400 W of heat to the Titan environment after landing [37]. Even with aggressive thermal control measures (which become progressively more difficult for small vehicles, since the area:mass ratio is higher at smaller scales, and the penetrations through insulation required for sensors, cabling etc. become proportionately more significant) steady-state operation on Titan's surface is impossible without tens of watts of thermal power – see section 8.1. Since the present suite of available RPSs is restricted to 100 W electrical systems, with thermal powers of 500-2000 W, the practical vehicle options bifurcate into long-lived platforms with a full RPS (making them by definition expensive and massive) and short-lived battery-powered platforms which, like the Huygens probe, operate on the combination of a thermal transient from an initial warm condition and sustained high power dissipation.

There is not space here to explore the operating parameters of a wide range of possible payload instruments, and

TABLE 2: *A Menu of Titan Balloon Options. Asterisk Denotes Concept was Developed After the 2007 NASA Titan Flagship Study*.

PASTA	PASsive TitAn balloon	Few kg. Hydrogen/Helium. Released from descent probe or lander. No power, instrumentation or communication. Tracked via foil radar reflector or passive transponder
BABA *	Battery Balloon	Few kg. Hydrogen/Helium. Released from lander, uses lander for data relay until thermal/battery expiry or over-the-horizon. Lifetime ~2-3 hours maximum. Payload as for ZORBA
SOBA *	Solar Balloon	Few kg – high altitude (~50 km+ only?) Hydrogen/Helium. Released from descent probe or lander. Long-lived, but operations only on dayside. Limited instrumentation – meteorologyhumidity/atmospheric optics only.
ZORBA and ZORBA-S*	ZOnal Recon BAlloon	~10-50 kg. One RPS (~100 We, ZORBA) or small RTG (0.5-10 We, ZORBA-S). Montgolfière (100 W only) or buoyant gas. Omnidirectional comm (DTE and relay).Payload ~5 kg: USO for groundbased tracking. Simple camera system. Altimeter. Meteorology (Sky brightness, Pressure, Temperature, Methane humidity) Minimal (no?) commanding.
TABI	TitAn Balloon Investigation	~100 kg Montgolfière. Active altitude control via vent valve. 1-2 RPS (100-200 We). 30 kg payload? Camera system, ground-penetrating radar. Aerosol collector and analysis laboratory. Meteorology.
TABASCO	TitAn BAlloon Survey and Collection of Organics	Similar to 2005/6 JPL 'TiPEX' study ~200 kg floating mass. 2 RPS double-wall Montgolfière. Active altitude control Steerable antenna for data relay. Tether/penetrator sample acquisition system and organic analysis laboratory. IR spectrometer, camera system, gound penetrating radar, meteorology, etc.
TALE	Titan Airship Latitude Excursion	Similar to 2005 JPL and Langley Visions studies. Buoyant gas airship with propulsion giving capability to traverse to different latitudes. 2 RPS. Steerable antenna for data relay. Tether/penetrator sample acquisition system and organic analysis laboratory. IR spectrometer, camera system, gound penetrating radar, meteorology, etc.

rational discussion of their science value makes little sense without considering the other platforms (e.g. orbiter, lander, another balloon, etc.) that might also be operating. Suffice it to say that there are power-hungry instruments that may demand many tens of watts (e.g. radars, spectrometers, chemical analysers) and there are other instruments with low operating powers of less than a watt (e.g. meteorological instruments, magnetometers). Similar ranges for masses and data rate can be envisaged. It is important to consider too that data volume and energy per acquisition may be the relevant parameters, rather than rates and powers. In other words, one does not leave a camera running continuously, but perhaps switches it on to acquire an image once per hour, during which time the balloon may have drifted about a camera-footprint across the surface (and at a typical few ~kbit/s datarate, it probably takes a commensurate period to transmit the data volume associated with one image). The operating duty cycle may therefore be very low (less than a tenth of a percent) in which case the warm-up time of the instrument is no less important than its steady-state power. This type of issue, and the details of the communication architecture, will drive the energy cost per bit of science data. In the absence of detailed designs (which can cause order-of-magnitude improvements or penalties), attention is drawn to our previous empirical rule-of-thumb, of "1 Joule, 1 bit" [11] - in other words, a system with a 1 We power source could likely return 100 kbits/day, or roughly one highly-compressed image.

3.1 New Options Permitted by Low-Mass RTGs

The 2007 NASA Flagship study considered only two available radioisotope power sources (RPSs), namely the MMRTG (MultiMission Radioisotope Thermoelectric Generator) and ASRG (Advanced Stirling Radioisotope Generator.) Both are ~100 We sources, with thermal outputs of ~2000 Wth and 500 Wth and masses of ~40 kg and 20 kg respectively. Given these parameters, it makes little sense to have a small (e.g. 2 kg)

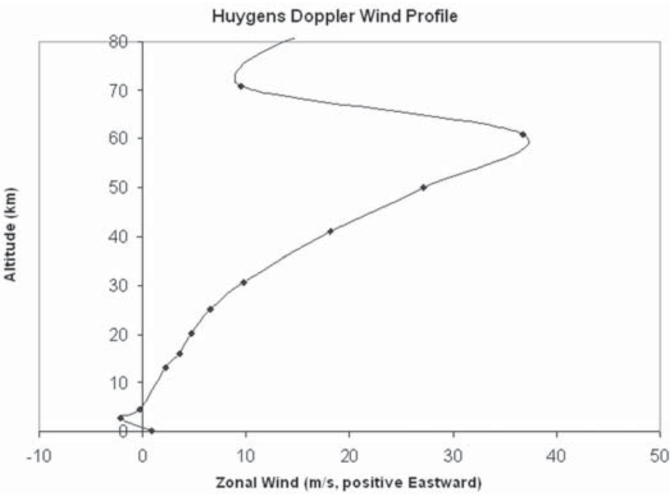

Fig. 2 The eastward motion of the Huygens probe during its descent at -10 degrees latitude in January 2005 (zonal winds will be different at other latitudes and seasons).

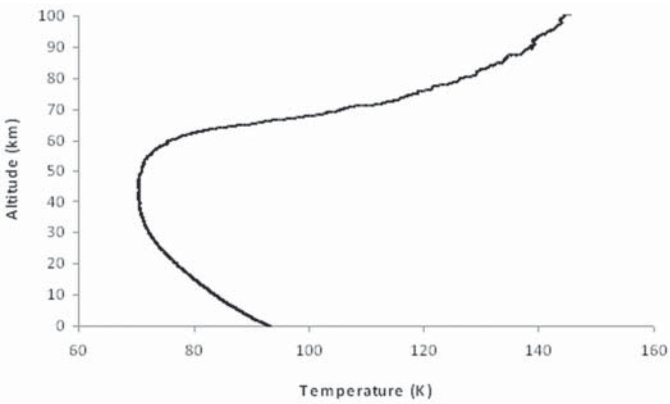

Fig. 3 Titan atmosphere temperature profile as measured by the Huygens Atmospheric Structure Instrument.

payload that consumes only a few watts, since the system mass is dominated by the coarsely-quantized power system. Or in other words, given the available power, while one could fly a small balloon with only a camera as payload, there is little reason not to also fly other more power-hungry experiments such as subsurface sounding radar or a pyrolzyer/gas chromatograph. Similarly, given that a 100 We power source must be carried (see below), it may as well act as a heat source for a Montgolfière, leading to the design solution proposed in the Flagship study.

However, as noted by the National Research Council's Committee on Space Science Missions Enabled by Nuclear Power and Propulsion [38], small radioisotope power sources of the 40 mWe-10We class could enable a range of new solar system missions, notably a set of small landers such as a Mars Long-Lived Lander Network able to perform low-data-rate but long-duration science tasks such as seismic and meteorological monitoring. Such power sources could also enable similar small landers at Titan with the same scientific goals, but would also enable small long-lived balloons at Titan with modest payloads. Such power sources would be ideal for a small version (ZORBA-S, see table 2) of a Titan balloon with a relatively lightweight but attractive payloads (e.g. radio tracking, meteorology and surface imaging : this is essentially the concept that was advanced with a never-realized 'Powerstick' RPS in the 1996 BETA balloon study [10]).

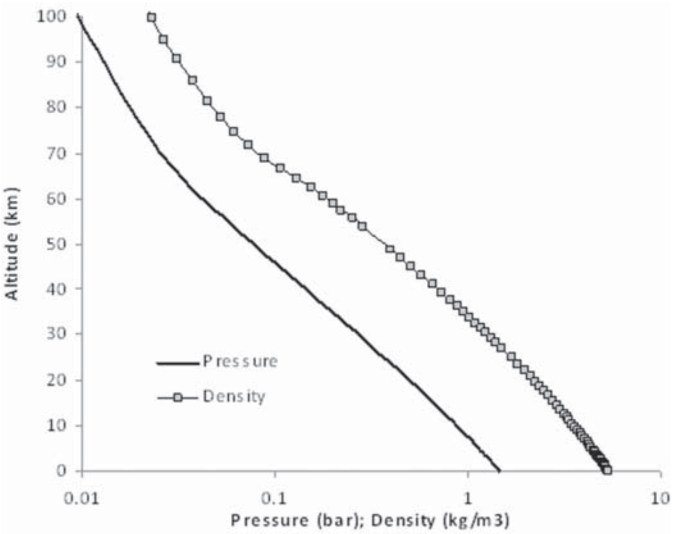

Fig. 4 Titan pressure profile measured by the Huygens Atmospheric Structure Instrument, and the density profile computed there from.

Designs for a variety of small radioisotope power supplies have been put forward [38] in the USA, although development of these has not been funded as yet. Small RTGs were also developed in Russia, and were flown on the Mars-96 mission [39, 40]. The Small Stations were each equipped with 2 RTGs and 2 RHUs, with a total mass of ~1.4 kg and electrical output of 440 mWe. The total thermal output was 8.5 Wth, from a PuO_2 burden of 120 g.

It may be noted that in addition to enabling small long-lived balloons, small RTGs could also permit a network of long-lived Titan surface science stations (e.g. able to make meteorological, seismological and magnetometer measurements together with some modest imaging) which could be distributed around Titan's surface by a balloon or delivered by individual entry vehicles.

4. BUOYANCY PERFORMANCE

Balloon performance in terms of payload mass fraction can be very different for the two basic balloon types, namely buoyant gas and hot air (or Montgolfière – NB the grave accent – the Montgolfier brothers named their balloon the Montgolfière, and the latter term is the appropriate one for this class of balloon; similarly, the hybrid balloon developed by Pilâtre de Rozier is termed a Rozière). These balloon types have different merits and performances in different planetary environments [38, 39] We show here that small payload, high altitude balloons are conveniently buoyant-gas, while large payload, low altitude balloons may be more efficiently realized as Montgolfières.

4.1 Buoyant Gas

For a buoyant gas (hydrogen or helium), the lofted mass relates to the volume (diameter cubed) of the envelope, while to a first order the mass of the envelope scales as its area (diameter squared). Thus generally a given payload/altitude target can be attained by making the balloon larger. As discussed in [39], for terrestrial balloons and typically at Titan and Venus, the balloon envelope mass is rather small (<10% of the payload), whereas on Mars, the large volume required at low pressure demands a large and therefore massive envelope (~30% of payload mass). However, particularly for low-altitude Titan balloons where the gas density is high, the mass of lifting gas can be significant, and in particular the tankage needed to store it is substantial.

In algebraic terms, a buoyant gas balloon with a payload (including gondola structure, communications and power source as well as the instruments themselves) M_p requires an envelope diameter D_b, for envelope areal density (specific mass) A_b. For gas molecular mass M_b and ambient molecular mass M_a, with ambient density ρ_a, we have

$$M_p + \pi A_b D_b^2 = (\pi/6)\rho_a((M_a - M_b)/M_a)\, D_b^3 \qquad (1)$$

However, in addition to the floating mass $M_p + \pi A_b D_b^2$, one needs to deliver to the floating location an additional mass, namely the gas mass $M_g = (\pi/6)\rho_a(M_b/M_a)\, D_b^3$ and a tankage mass $M_t = K_t M_g$.

For the purposes of discussion, we consider two candidate altitudes – 8 km (at which altitude the Huygens probe showed that surface imaging is readily feasible, yet is safely above the terrain) and 60 km, in the lower stratosphere above any methane weather but below the stratospheric wind minimum: at 60 km the ~35 m/s zonal winds (Fig. 2) would sweep the balloon around Titan in about 4 days. The density ρ_a for these altitudes are 3.9 and 0.18 kgm^{-3} respectively (Fig. 4), temperatures being 84 and 77K (Fig. 3). Typical values for A_b ~0.02 to 0.3 kgm^{-2} and for K_t are 5-10: further discussion on these quantities follows. The interested reader is also referred to the wide literature on terrestrial balloons (e.g. [41]).

The VEGA balloons at Venus had a rather heavy construction, with A_b~0.3 kgm^{-2} - at the other end of the spectrum, very lightweight and thin materials used in terrestrial stratospheric balloons can have A_b less than 0.04 kgm^{-2}. Even in the early 1980s [42] some detailed consideration of Titan balloon materials was made such as two or three-layer laminates (i.e. film-mesh and film-mesh-film) of 20-micron polyester film with a polyester mesh, with weights of 0.050 to 0.075 kgm^{-2} or a five-layer laminate of a 12.5-micron aluminized Polyvinyl fluoride (PVF - 'Tedlar') film with a polyester adhesive and a polyester mesh, with a weight of 0.047 kgm^{-2}. The PVF film had the best low-temperature properties, while polypropylene has a lower density lending itself to balloon fabrication. Polyester had poorer properties, but has the advantage of being a well-known material to balloonists. More recently, Hall *et al.* [17, 20] report strength/fatigue flex testing on possible envelope materials for Titan. A moderate weight laminate (polyester film and polyester fabric) had a specific mass of 0.094 kgm^{-2} and an ample pull strength of 9100-16400 N/m at 298 and 77K respectively. Thus 0.1 kgm^{-2} is a reasonably conservative value to adopt.

For advanced tankage and small masses K_t~4, but will typically be higher. A large carbon-filament-wound tank displayed at the 2007 Paris Air Show has a capacity of 180 l and a mass of 40 kg: at its rated pressure of 300 bar it could hold 9 kg of Helium, i.e. Kt of a little over 4. (As a point of reference, one rule-of-thumb [43] used in the design of spherical titanium pressurant tanks for spacecraft is M = 0.0116PV, where M is the tank mass in kg, P is the tank pressure in kPa and V its volume in m^3. For a 25 m^3 balloon to provide 100 kg of lift at Titan at 85 K about 15 kg of He is required, and the room temperature PV product (the system must be storable under terrestrial conditions before launch!) gives a tankage mass of ~116 kg, or K_t~7. The study by Friedlander (1985) assumed kevlar-wound stainless steel tanks and hydrogen lift gas: some 90 kg of tankage and fill system for 10 kg of buoyant gas, or K_t~9.

Equation (1) can be solved iteratively and yields results summarized in Figs. 5 and 6 although when the envelope mass is small as here, regardless of float altitude, the delivered mass in roughly $M_p[1 + (K_t + l)(M_b + M_a)]$.. Figure 5 shows the comparative insensitivity of low-altitude Titan balloons (especially buoyant gas balloons at low altitude) to envelope specific mass. Figure 6 shows that assuming the same K_t performance, hydrogen is a much more efficient lifting gas than helium – while the envelope mass is tiny in both cases, the mass of has required and its tankage is significant, making the delivered mass (gas, tankage, envelope and payload – all of which must be delivered inside an entry heat shield) double the paylaod mass for hydrogen, and nearly triple for helium.

A perhaps unexpected result is that since the balloon envelope mass is so small, these factors of 2-3 apply essentially the same for low-and high-altitude balloons – i.e. even though at low altitude the air density is high, so balloon volume is small, the buoyant gas density is also high so a large gas and tankage mass is still required. Thus to float an 80 kg payload at 8 km with hydrogen or helium and an envelope mass of 0.1 kgm^{-2} requires a ~3.6 m balloon with an envelope mass of only 4 kg, but a gas mass of 6-14 kg and a tankage mass of some 50-110 kg. (As a point of reference, the VEGA balloons [9] had a gondola mass of 7 kg, required 2 kg of Helium and had a 12.5 kg balloon envelope and tether mass.)

4.2 Montgolfière Performance

Although, as is well known, hot air has a lower specific buoyancy than hydrogen or helium (since realistically temperatures cannot exceed the environmental temperatures by more than a small factor, the density ratio is always close to one), a Montgolfière performs particularly well on Titan due to the low temperature of the environment. This has two effects – first, following the ideal gas laws, the buoyancy per cubic meter given for each temperature increment (superheat) of 1 degree K is 3 times larger at 94 K than at 273 K. Second, the thermal power required to sustain a given superheat is far lower than at Earth, due to the highly nonlinear relationship of radiative heat flux to temperature. At low temperatures the heat loss is rather modest, being dominated by free and forced convection which are simply proportional to the temperature difference (ΔT, or 'superheat') between internal air temperature T_i and the ambient temperature T_a. This is in contrast to the much higher radiative loss $\sigma(\varepsilon T_i^4 - T_s^4)$ which dominates for terrestrial balloons

Thus, for a noninsulating single-walled Montgolfière (where the balloon envelope itself does not inhibit heat transfer), the heat loss will be proportional to the temperature difference and the area (diameter squared) of the envelope. The buoyancy will be proportional to the volume (diameter cubed) and the temperature difference.

For a Montgolfière of diameter D_m on Titan in steady-state conditions we have a thermal power P that balances the convective heat loss, parameterized as a heat transfer coefficient h, such that $P = \pi D_m^2 h(T_i - T_a)$. Typical heat transfer coefficients h at the balloon scale with superheats of a few to 20 degrees are of order ~1 $Wm^{-2}K^{-1}$ (heat transfer coefficients scale down as size increases, so this value is lower than that measured by the Huygens probe. Note also that a balloon that is not actively manoeuvring will tend to have a lower relative velocity to the air than a parachute-borne probe, and thus lower forced convection.)

Terrestrial hot air balloons have ample thermal power P, in that a propane burner is operated at a low duty cycle (a few

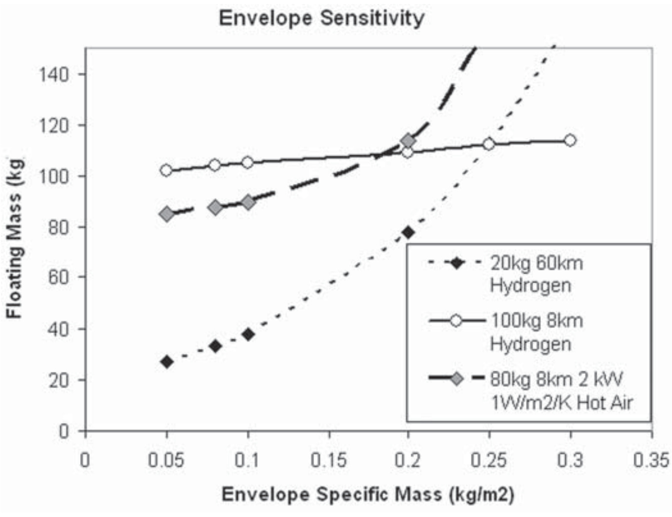

Fig. 5 For a tropospheric hydrogen balloon, and a tropospheric hot air balloon well within performance limits, float mass is relatively insensitive to envelope material density. For hot air near its limit, and for a stratospheric hydrogen balloon, envelope specific mass becomes a significant factor.

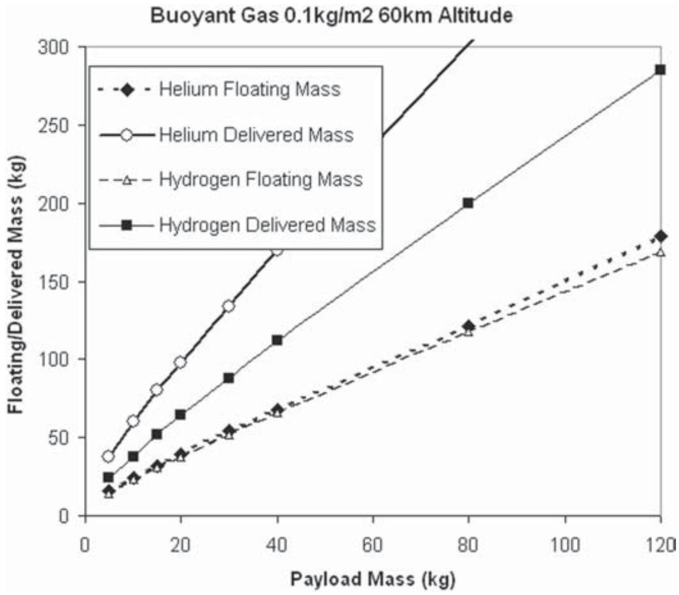

Fig. 6 Stratospheric buoyant gas balloons have envelope masses that are small relative to the payload. Delivered mass (float mass plus gas and tankage) is sensitive to choice of fill gas, with hydrogen offering superior performance assuming tankage fraction is the same for both (8 kg/kg).

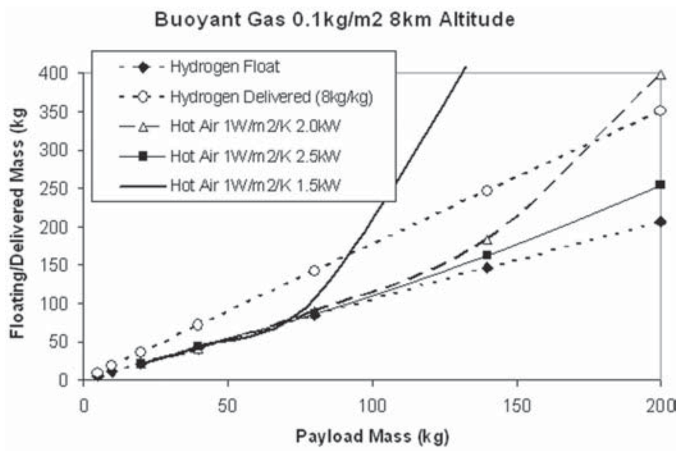

Fig. 7 Mass Tradeoff between Hot air and buoyant gas for tropospheric balloons. Until the hot air performance threshold is reached (~200 kg for 2 kW and 1 W/m2/K) the hot air balloon has a comparable float mass but much lower delivered mass than a hydrogen balloon.

seconds every few minutes): performance is limited by the highest temperature the balloon material can tolerate (see later) and the balloon is sized smaller than the thermal optimum in order to be more manoeuvrable, and more easily deployed and stowed on a truck or trailer. For a Titan Montgolfière with a continuous radioisotope heat source, the situation is thermal power-limited. Making the balloon larger ultimately has no effect, in that increasing the balloon volume indeed allows more lift for a given superheat, but also increases the area over which heat is lost so that the superheat that can be sustained for a given power declines (there is a scale effect in the heat transfer coefficient, but this is small). When the heat transfer coefficient is held constant, it can be shown [44] that there is a theoretical maximum payload mass, given approximately by $M_{p\_max} = (1/144\pi)(1/A_m)(P\rho_a/hT_a)^2$ with the balloon diameter $D_m = (\rho_a P)/(12\pi h T_a A_m)$.

Thus, substituting some typical values for floating at 8 km altitude with the 2 kW thermal output of a MultiMission Radioisotope Thermoelectric Generator (MMRTG) $\rho_a = 3.9$ kgm^{-3}, P= 2 kW, h =1 Wm^{-2}K^{-1} , $T_a = 85$ K, $A_m = 0.1$ kgm^{-2} , we obtain $M_{p\_max} = 195$ kg, although note that this is an idealized maximum – practical designs should consider masses a factor of two or so lower –see below.

In the lower atmosphere, Montgolfière balloons are generally more mass-efficient than light gas balloons (e.g. see Fig. 7), although there is a steep rise in Montgolfiere floating mass as the theoretical maximum payload is reached. The superior lift performance occurs mainly because a Montgolfière does not need to carry its own gas and tankage: there are of course other advantages such as robustness and the ease with which altitude can be controlled.

The sensitivity of required float mass to payload for various values of thermal power can be seen in Fig. 7 – up to about 75% of the optimum value the envelope mass is small, while at the optimum the envelope mass equals the payload. Thus a realistic design will be derated by a factor of 2 or so from the optimum value, such that a 2 kW heat source can realistically support only ~100 kg. Factors that should be considered in developing this derating margin are that, for example, approximately 25% of the heat output of the propane burners in terrestrial hot air balloons is lost from the balloon as hot air from the flame displaces air that is warmer than the ambient or that the typical inverted teardrop shape of an inflated and loaded balloon with a narrow vent actually has a surface area, and thus heat loss area and balloon envelope mass, 20% or so higher than a perfect sphere with the same enclosed volume.)

It can be seen by the squaring in the last term in the expression for optimum mass that the performance is particularly sensitive to the heat transfer coefficient, but rather less sensitive to typical values of the envelope specific mass. This can be seen in Fig. 8 for a 2 kW (1 MMRTG) Mongolfiere at 8 km. One approach to mitigate this sensitivity may be to use a double-walled Montgolfière – such that there is in effect an insulating barrier between the inside and outside of the balloon. Double wall balloons have been demonstrated on Earth, and indeed Roziere designs such as the Breitling Orbiter III which

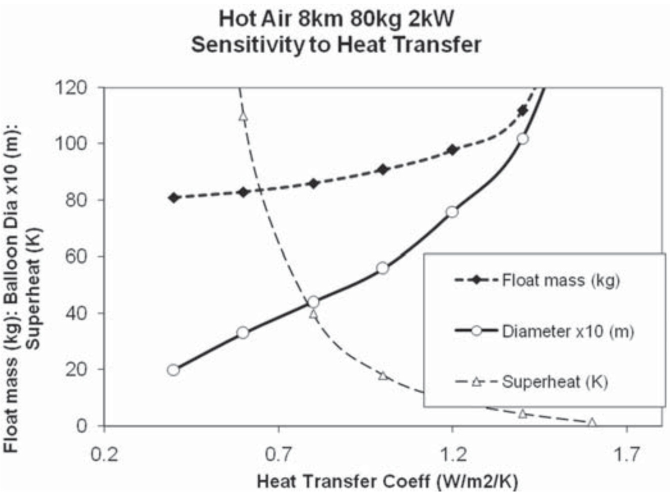

Fig. 8 Hot air balloon parameters are acutely sensitive to assumed heat transfer coefficient. For nominal performance (~1 W/m2/K) the required balloon diameter is ~8m with a superheat of ~20 K.

made a 20-day round-the-world flight in 1999 in effect are double-wall. (It is interesting to recall the British Interplanetary Society's Daedalus study of an interstellar vehicle, which would use nuclear-powered balloon platforms in the Jovian atmosphere to obtain propellant : it was noted then that double-walled Montgolfieres were appropriate in that situation which similarly used waste heat to provide buoyant lift [45]) Note that Montgolfières are not feasible for stratospheric operation on Titan: the very large air volumes required demand large balloons and thus large heat loss areas.

5. GONDOLA AND ENVELOPE THERMAL CONSIDERATIONS

The lower atmosphere of Titan is somewhat opaque to thermal radiation, and is dense. These factors make it impossible for any surface of the gondola to remain out of equilibrium with its immediate surrounds for long without substantial internal heating. (As a point of comparison, the 1.3 m diameter 200 kg Huygens probe, with a layer of 5 cm of insulating foam, was losing ~400 W of heat to its environment near the surface.)

The 2007 NASA Flagship study (Fig. 9), in the interests of expedience, suggested separating the balloon buoyancy function (placing a 2 kWth source in the neck of the balloon, and having a separate source for gondola heat and electrical power). Some creative thinking in the future may generate suitable designs wherein a single radioisotope source such as an MMRTG can supply heat to the balloon hot air with sufficient robustness to assure flotation, as well as supply electrical power (subject to the cold-end temperatures of its thermoelectric converters, which in turn will depend on how it is coupled to the air and gondola) and keep the gondola warm.

Balloon altitude excursions can occur due to day:night variations in solar heating of the balloon, especially at Earth and Mars. However, in Titan's lower atmosphere, the noontime sunlight flux is only about 1.5 Wm^{-2} (since the upper atmospheric haze screens out most (~90%) of the incident sunlight, which is in turn nearly 100 times weaker than sunlight at Earth) thus a relatively insignificant increment over the likely required thermal power (i.e. the balloon will experience at most rather modest altitude excursions due to diurnal heating/cooling.)

Note that while the balloon envelope operates at a low temperature, it does not have to be deployed at a low temperature, since the envelope, gondola and radioisotope heat source will be packaged together in an entry shell. A further note needs to be made – while one might design a buoyant gas balloon to operate at ambient temperatures, if the gondola has a radioisotope power source, then some of the waste heat may be convected onto the balloon envelope, affecting its buoyancy (or in the case of a superpressure balloon, the pressure). Any uncertainties in the amount of this heating would need to be taken into account.

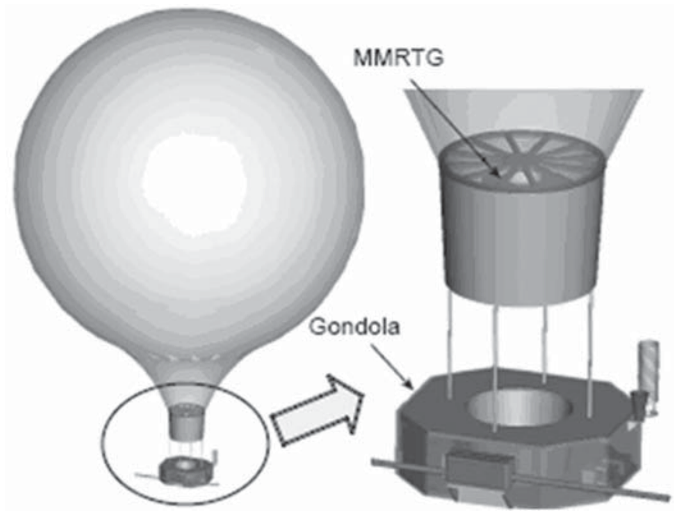

Fig. 9 The Montgolfière concept from the 2007 NASA Flagship study. To maximize the efficiency of heat delivery into the envelope, the 2 kWth MMRTG was mounted in its neck. This therefore heating of the gondola by a separate RPS.

6. BALLOON LONGEVITY – A YEAR AT TITAN IS EASY

Assuming a balloon is not directly overstressed e.g. by ascending too high, entering a thunderstorm or crashing into the ground, its lifetime can be very long. On Earth, a life-limiting factor in balloon envelopes is the degradation of the polymers by ozone or solar ultraviolet light: this would not be a concern for Titan which is a reducing environment with no ozone and where ultraviolet light is (a) weaker due to distance from the sun and (b) absorbed at very high altitudes by gases and haze anyway.

Buoyant gas balloons are often limited by gas diffusion through the envelope material (although the low temperatures at Titan will slow this effect down compared to Earth), and/or by gas leak through pinholes or tears. Montgolfière balloons have essentially no practical lifetime limit. Commercially-made envelopes are usually formally rated for 600 hours flight time (i.e. ~200 inflation/packing cycles) but it is well-known that appropriate care (e.g. use of groundsheets to exclude dirt from a packed envelope) will permit longer use. Another factor on terrestrial Montgolfière lifetime is the degradation of the sealant used on the fabric. The sealant longevity (factored into the rated lifetime above) typically assumes that the envelope temperature is as high as 125°C, this temperature limit defining the lift performance of a given envelope. Operation at lower temperatures yields much slower degradation.

It may be noted that Montgolfière envelope lifetime is not typically curtailed by catastrophic failure but rather by graceful degradation: a damaged envelope just requires more fuel to fly, or flies lower for a given heat supply. Pinholes or even small tears are not catastrophic. Thus retirement of an envelope is usually a question of economics rather than a safety consideration: Continued Airworthiness Requirements (CAR) allow ½ -inch holes in the upper part of envelope to remain unrepaired until the next annual inspection.

Since a Titan balloon need be inflated only once (plus a few times for ground testing) and thus sees few stressing cycles, has no UV degradation and can operate at low temperatures, it seems that its lifetime could easily be several years.

7. IN-AIR INFLATION

While inflation in mid-air is not typically encountered in recreational ballooning, it should be remembered that in fact the modern incarnation of the hot air balloon (nylon fabric, propane burners) owes its development to a US military effort to develop a Pilot Escape and Survival System [25] by which pilots ejecting from aircraft over enemy territory could deploy a balloon in mid-air, heat it to buoyancy, and thereby remain safely aloft until a mid-air retrieval could be effected by a friendly aircraft. Although the system was never fielded, it is under this program that nylon envelopes and the propane burner that characterize modern recreational ballooning came about.

Although there are few published details, it should also be noted that the airborne deployment of jamming pods suspended under a ballute have been demonstrated (see e.g. [46]). The pod is released from a fast-moving aircraft and a trailing ballute is deployed much as for retarded bombs. In this instance, however, the ballute is rather larger. Once it has inflated and the pod decelerated into terminal vertical descent, a pyrotechnic charge is actuated to heat the air in the ballute which now functions as a balloon, allowing the jamming pod to loiter over the target area for far longer than a simple parachute would permit.

Clearly, in-air inflation and heating is an operation that would need to be refined and demonstrated on Earth during the development of a Titan balloon system, but the operation appears rather straightforward. The vertical extent and density of the Titan atmosphere is very forgiving in the sense of allowing considerable time to perform inflation and buoyancy attainment.

8. NON-NUCLEAR BALLOON OPTIONS

As discussed in the context of 1 Joule/1 bit, the scientific return correlates with the energy available, making radioisotope powered options most attractive since these can support sophisticated instruments and large data volumes. In the interests, however, of articulating the full spectrum of options for Titan, a few non-nuclear options can be mentioned.

8.1 Battery-Powered Balloon

This may be thought of as a variant of a conventional probe like Huygens – indeed without the staging of Huygens' main (8.3 m diameter) parachute for a smaller 'stabilizer', the probe descent would have taken some 5 hours or more. In the case of a longer flight under a buoyant gas balloon, the thermal lifetime will likely be the limiting factor.

Primary batteries such as those on Huygens have an energy density of ~200 W-hrs per kg. Operation of a small set of instruments might be accomplished with a dissipation of a watt or two, with a larger payload requiring some tens of watts, while telecommunications (perhaps operated at a low duty cycle – a Titan orbiter would be visible from a balloon or lander on Titan for some tens of minutes every few hours, depending on the orbital geometry) would likely require some tens of watts. If we adopt, say 30 W as a steady-state power consumption, we can equate this to a steady-state heat loss.

We assume the interior of the gondola to be sufficiently warm (at 273 K, say) for batteries to function well. The exterior is at 84 K, or a 189 K temperature difference. For steady state, we require the conductive heat loss to balance the dissipation, or for a surface area A, insulation thickness t and conductivity k, $30 = 189\ Ak/t$. Now, the foam insulation used on Huygens had a conductivity of the order of 0.02 $Wm^{-2}K^{-1}$. If we imagine a 20 kg gondola with a density of 500 kgm^{-3} (a typical value for spacecraft – the denser the unit can be built, the lower the heat loss area), then it has a volume of 40 litres, and thus could be approximately a cube of 40 cm on a side. The corresponding loss area is about 1 m^2 and so for the heat to balance, the insulation must have a thickness of t~13 cm. This is bulky but not unfeasible. If we devote 50% of the mass to batteries, allowing 10 kg for structure, instruments, data handling, radio etc., then we have 10 kg or 2000 W-hrs, allowing this system to operate at 30 W for 70 hours, or about 3 days.

Clearly higher-power operation is possible for shorter duration, and would allow thinner insulation. Operation for longer periods is problematic, in that the low power dissipation would require very thick insulation for steady-state (in fact, one operating mode that would be robust to thermal uncertainties is to adapt the data acquisition and transmission duty cycle in order to achieve thermal balance – i.e. if the system senses its temperature is dropping, take another picture and transmit it to stay warm.) It is not clear that more advanced insulation such as a dewar would help in overall performance, in that there must still be penetrations for antennas and instruments, which will tend to thermally short-circuit the overall insulation. However, such advanced approaches might allow more compact packaging.

This thermal problem (confronted, in another form, by warm-blooded animals [47]) favours large scale, in that the heat loss area goes up as the square of size, but the energy storage volume goes up as the cube of size. Thus a 200 kg gondola with insulation of the same thickness as above would have a heat loss area ~5 times larger and thus would require 5 times more power for steady state, but with the same battery mass fraction could hold ten times the energy. Thus it could operate for twice as long, while sending back data at a rate 5 times higher (using the 1J/bit metric, a 10 kg battery provides 2000 W-hr, or 7.2 MJ/7.2 Mbit; a 100kg battery provides ten times this. For reference, the total Huygens data return was of the order of 100 Mbit via Cassini relay, while the VEGA balloons with 250 W-hr returned about 40 kbit total with Direct to Earth communication).

Correspondingly, a 2 kg gondola is essentially unworkable in Titan's troposphere, and since the required thermal powers are some tens of watts, radioisotope heater units (typically 40 g, 1Wth each) are too weak or heavy for such small systems. Logically a small system should have radioisotope electrical power for longevity beyond a few hours: a 2 kg gondola could, by the scaling above, be kept warm with 5-10 Wth, commensurate with the Mars-96 0.44 We small RTG discussed in section 3.1 or perhaps with similar sized devices with higher conversion efficiency. (Note that the VEGA balloons carried a 1 kg 250 W-hr lithium battery, and operated for 48 hours – but the thermal environment there was benign: no energy had to be expended to maintain operating temperature.)

8.2 Unpowered Balloons

Although only yielding information on air density and wind, the 'minimum' end of the balloon spectrum may be defined by a purely passive balloon, carrying a foil cube-corner radar reflector.

Such a balloon could obviously be inflated and released from a lander. Conceivably, however, it may be possible to deliver an inflated balloon from orbit – given its extremely low mass loading and the large scale height in Titan's atmosphere, the deceleration and thermal loads would be very small. The disadvantage, of course, is that the location of the balloon immediately post-entry would be difficult to predict.

During a balloon's buoyant ascent (or its descent, if deployed at high altitude – balloons of this type (Fig. 10) were deployed on Earth by sounding rocket in 1965 – [48]) its motion at terminal velocity yields information on density: after attaining its float altitude it acts as a wind tracer. It should be possible to give an imaging radar or altimeter on an orbiter the ability to detect the echo from such a balloon, although contacts with a given balloon will not occur very frequently.

8.3 A Solar-Powered Balloon

As discussed earlier, vehicles without radioisotope power are condemned to a short thermal lifetime in the thick, cold, dark troposphere. However, in the stratosphere, above much of the haze, it may be possible to capture enough sunlight with a large area solar array to conduct long-term science operations – Huygens measurements show, for example, aroughly four-fold increase in solar flux at ~60 km altitude compared with the lower troposphere (10 km and below) – see Fig. 11.

A high-altitude balloon would logically be of low mass, and carry a minimal payload (perhaps at most only atmospheric structure instrumentation and some simple optical properties and chemical abundance measurements, since strong compositional gradients may exist in this altitude, perhaps only a periodic radio beacon as a minimum.) The relatively thin air at these altitudes makes it easier to control the temperature of balloon equipment by radiative coatings, such that at least daytime operation of equipment may be possible without radioisotope heating – this gets easier the higher the altitude.

Whether such a vehicle could be kept warm enough and/or have a sufficiently positive power budget to permit use of an ultracapacitor for nighttime sensor operations will require further study. The energy budget afforded by solar power is unlikely to permit sufficient communications bandwidth to support imaging (imaging of the surface by a small camera would in any case be somewhat compromised by the high altitude and the long haze column between the balloon and ground) but rudimentary VEGA-like measurements and tracking by Doppler and/or VLBI techniques would nonetheless be scientifically appealing, given the relatively modest cost of such a vehicle.

Detailed modelling of the shortwave fluxes and the corresponding low-temperature efficiency of a (thin-film, flexible?) solar array would be needed to assess the energy budget. Radiative transfer calculations would be similarly required to evaluate the feasibility of achieving at least temporarily a warm enough gondola for operations; the potential degradation of optical coatings by condensation of organics or the deposition of haze would need to be taken into account. This section is merely the statement that it is not impossible to contemplate a limited solar balloon at Titan, at high altitudes, but much more work is needed to show that such a system is in fact feasible.

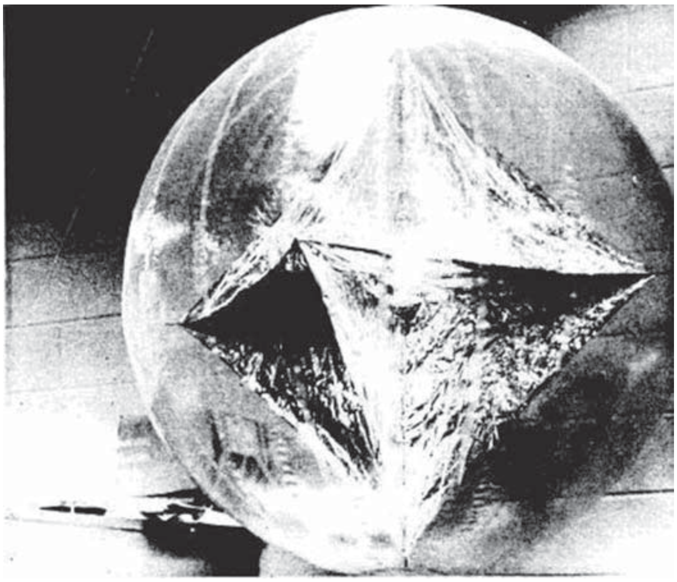

Fig. 10 A possible minimal balloon for Titan: an entirely passive helium-filled sphere with a foil radar reflector. A balloon of this type was deployed from a sounding rocket on Earth (Peterson, 1965).

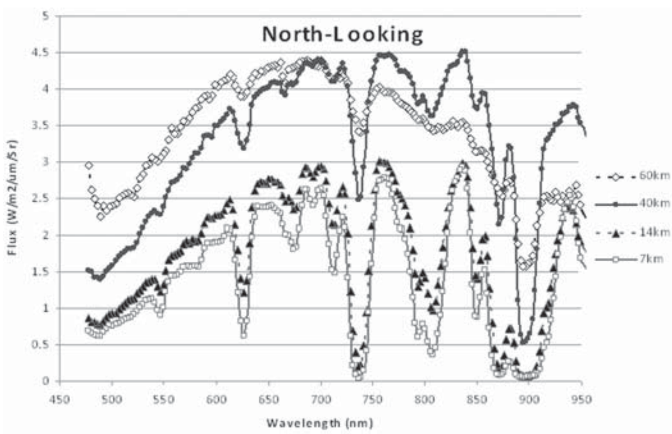

Fig. 11 Upward-looking visible and near-IR fluxes recorded by the Huygens probe DISR instrument. (PDS Dataset ID HP-SSA-DISR-2/3-EDR/RDR-V1.0 ULVS_DDP.TAB). Flux is relatively insensitive to altitude in the lower troposphere, but is rather higher at 40-60 km.

9. CONCLUSIONS

The thick, cold atmosphere and outstanding scientific richness of Titan make it a very attractive target for a balloon mission. A wide variety of balloon options exist, adaptable to whatever cost/risk posture is adopted by the relevant agency or agencies. A key factor is the power supply, which presently drives many design solutions to a large (100-200 We, 100-200 kg) platform able to support a large scientific payload. Given the thermal output of such a radioisotope power supply, plus the advantages of longevity, weight performance and the easy inclusion of altitude control, a Mongofliere is the logical type for such a vehicle. Such a vehicle could be augmented by propulsion and even surface sampling.

Battery-powered buoyant gas balloons of a range of sizes are possible for both the troposphere and stratosphere, but have a longevity of at most a few days, with a commensurately low data return. While challenging, an ultra-lightweight solar-powered or completely passive high altitude balloons may be feasible.

Finally, an attractive part of option space that has not yet been explored in detail is that of small (50 mWe-10 We) radioisotope power sources carried by a simple buoyant gas balloon. Such a platform could be capable of surface imaging of different parts of Titan's diverse surface, and could have a lifetime of some months depending on gas diffusion rates, but would be relatively inexpensive.

ACKNOWLEDGMENTS

The Titan Flagship Mission study ('Titan Explorer") was undertaken via a contract from NASA and was led by James Leary, Mary Kae Lockwood and the present author at APL: the support of JPL, NASA Langley, ILC Dover and the Science Definition Team is acknowledged. Discussions over many years on Titan ballooning with Jeff Hall, Tibor Balint, Tom Spilker, Kim Reh, Wayne Zimmerman, Jack Jones, Jim Cutts, Jonathan Lunine and Julian Nott are acknowledged.

REFERENCES

1. R.D. Lorenz and J. Mitton, "*Lifting Titan's Veil*", Cambridge University Press, 260p, 2002.
2. A. Coustenis and F. Taylor, "*Titan - The Earth-Like Moon*", World Scientific, 1999
3. R.D. Lorenz and J Mitton, "*Titan Unveiled*", in production with Princeton University Press for publication in 2008
4. Martin Marietta Corporation, "A Titan Exploration Study: Science, Technology and Mission Planning Options", NASA CR-137846, 1976.
5. J. Blamont, "A Method of Exploration of the Atmosphere of Titan", pp.385-395 in D. M. Hunten and D. Morrison (eds), *The Saturn System*, NASA Conference Publication 2068, 1978
6. A.L. Friedlander, "Titan Buoyant Station", *JBIS*, **37**, pp.381-387, 1984.
7. A.L. Friedlander, "Buoyant Station Mission Concepts for Titan Exploration", 36th International Astronautical Federation Congress, Stockholm, Sweden, 1985. Paper No. IAF-85-417.
8. R.D. Lorenz and K.T. Nock, "BETA - Balloon Experiment at Titan", Proceedings of the 2nd International Conference on Low-Cost Planetary Missions, Laurel, MD, USA, 16-19 April 1996. Paper No. IAA-L-0601.
9. R.S. Kremnev and the VEGA Balloon Science Team, "VEGA balloon and instrumentation", *Advances in Space Research*, **7**, pp.307-310, 1987.
10. R.Z. Sagdeev *et al.*, "Overview of VEGA Vebnus Balloon in Sity Meteorological Measurements", *Science*, **231**, pp.1411-1414, 1986.
11. R.D. Lorenz, "Post-Cassini Exploration of Titan: Science Rationale and Mission Concepts", *JBIS*, **53**, pp.218-234, 2000.
12. R.D. Lorenz, J.I. Lunine and W. Zimmerman, "Post-Cassini Exploration of Titan : Science Goals, Instrumentation and Mission Concepts", *Advances in Space Research*, **36**, pp.281-285, 2005.
13. JPL, *Titan Vision Mission Study,* http://www.lpi.usra.edu/opag/oct_05_meeting/jpl_titan.pdf. (Downloaded 1 November 2007)
14. J. Levine *et al.*, NASA LaRC Visions Missions Study, http://www.lpi.usra.edu/opag/oct_05_meeting/langley_titan.pdf. (Downloaded 1 November 2007)
15. E.C. Sittler *et al.*, Titan Orbiter Aerover Mission (TOAM), 4th International Planetary Probe Workshop, Pasadena, CA, 2006. https://ippw.jpl.nasa.gov/20070607_doc/4_16SITT.pdf
16. K. Reh *et al.*, *Titan Prebiotic Explorer (TiPEx) Mission Study Final Report,* Jet Propulsion Laboratory, Pasadena, CA, 2007.
17. J.L. Hall, V.V. Kerzhanovich, A.H. Yavrouian, J.A. Jones, C.V. White, B.A Dudik, G.A. Plett, J. Mennella and A. Elfes, "An Aerobot for Global In Situ Exploration of Titan", *Advances in Space Research*, **37**, pp.2108-2119, 2006.
18. A.K. Noor, J.A. Cutts and T.S. Balint, "Platforms for Discovery: Exploring Titan and Venus", *Aerospace America*, pp.32-38, June 2007.
19. A. Elfes, J.A. Hall, J.F. Motgomery, C.F. Bergh, B.A. Dudik, "Toward a Substantially Autonomous Aerobot for Titan Exploration", AIAA 2003-6714, AIAA 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Tech Denver, Colorado, 17-19 November 2003,
20. J.L. Hall, J.A. Jones, V.V. Kerzhanovich, T. Lachenmeier, P. Mahr, M. Pauken, G.A. Plett, L. Smith, M.L. Van Luvender and A.H. Yavrouian, "Experimental Results for Titan aerobot thermo-mechanical subsystem development", *Advances in Space Research*, in press, 2007.
21. V.V. Kerzhanovich and J.L. Hall, "Major Progress in Planetary Aerobot Technologies", IEEEAC paper #1492, IEEE Aerospace Conference, Big Sky, MT., March, 2007
22. M. Lockwood, "Titan Aerocapture Systems Analysis", AIAA-2003-4799, AIAA/ASME/SAE/ASEE39th Joint Propulsion Conference, Huntsville, Alabama, July 2003.
23. A.A. Pankine, K.M. Aaron, M.K. Heun, K.T. Nock, S.R. Schlaifer, C.J. Wyszkowsky, A.P. Ingersoll and R.D. Lorenz, "Directed Aerial Robot Explorers (DARE) for Planetary Exploration", *Advances in Space Research*, **33**, pp.1825-1830, 2004.
24. T. Tokano and R.D. Lorenz, "GCM Simulation of Balloon Trajectories on Titan", *Planetary and Space Science*, **54**, pp.685-694, 2006.
25. D. Owen, "*Lighter than Air*", Quintet Publishing, London, 1999.
26. J. Nott, "Design considerations and practical results with long duration systems for manned world flights", *Advances in Space Research*, **33**, pp.1667-1673, 2004.
27. http://www.parallax.com/html_pages/resources/custapps/app_nearspace.asp. (Dowloaded 1 November 2007)
28. B. Ellison, J. Giammanco, T.G. Guzik, K. Johnson and J.P. Wefel, "The Louisiana ACES student-built BalloonSat program", *Advances in Space Research*, **38**, pp.2253-2258, 2006.
29. S. Businger, R. Johnson and R. Talbot, "Scientific Insights from Four Generations of Lagrangian Smart Balloons in Atmospheric Research", *Bulletin of the American Meteorological Society*, **87**, pp.1539-1554, 2006.
30. G.E. Dorrington, "Development of an airship for tropical rainforest canopy exploration", *The Aeronautical Journal*, **109**, pp.361-???, 2005.
31. W. Herzog (director), *The White Diamond*, MarcoPolo Films, 2005. See also http://www.dendronautics.org/.
32. J. Leary *et al.*, "Titan Explorer Flagship Mission study", Johns Hopkins University Applied Physics Laboratory, 2007.
33. R.D. Lorenz, "Scaling Laws for Flight Power of Airships, Airplanes and Helicopters: Application to Planetary Exploration", *Journal of Aircraft*, **38**, pp.208-214, 2001.
34. J.F. Gasbarre, H.S. Wright and M.J. Lewis, "A Design Comparison of Atmospheric Flight Vehicles for the Exploration of Titan", AIAA 2005-6235, AIAA Atmospheric Flight Mechanics Conference and Exhibit, San Francisco, CA., 15-18 August 2005.
35. R.D. Lorenz, J. Leary, M.K. Lockwood and J.H. Waite, "A Titan Flagship Mission", STAIF Conference Proceedings, Albuquerque, February 2008.
36. R.D. Lorenz, "Titan Bumblebee: A lander-launched UAV", in preparation
37. R.D. Lorenz, "Thermal Interaction of the Huygens Probe with the Titan Environment: Surface Windspeed Constraint", *Icarus*, **182**, pp.559-566, 2006.
38. National Research Council, Priorities in Space Science Enabled by Nuclear Power and Propulsion, National Academies Press, Washington DC, 2006
39. A.J. Ball, J.R.C. Garry, R.D. Lorenz and V.V. Kerzhanovich, "*Planetary Landers and Entry Probes*", Cambridge University Press, 2007.
40. R.D. Abelson (ed), "*Enabling Exploration with Small Radioisotope Power Systems*", JPL Publication 04-10, Jet Propulsion Laboratory, Pasadena, CA, September 2004.
41. A.L. Morris, "Scientific Ballooning Handbook", NCAR-TN/IA-99, National center for Atmospheric Research, Boulder, CO, May 1975
42. C. Sable and J. Villaeys, "Choix des materiaux d'Enveloppe pour Vehicules D'Exploration Planetaire (Venus-Mars-Titan)", Proceedings of an International Symposium on Spacecraft Materials in Space Environment, Toulouse, 8-12 June 1982, European Space Agency SP-178, Noordwijk, The Netherlands, 1983.
43. C.D. Brown, "Elements of Spacecraft design", American Institute of

Aeronautics and Astronautics, Reston, VA, 2002.
44. R.D. Lorenz, "Linear Theory of Optimum Hot Air Balloon Performance – Application to Titan", *The Aeronautical Journal*, submitted.
45. R.C. Parkinson, "Project Daedalus, Propellant Acquisition Techniques", *Project Daedalus – Final Report*, British Interplanetary Society, S83 – S89, 1978.
46. J. Nott, "Ballutes – Launching balloons without compromises", International Planetary Probe Workshop, Pasadena, California, June 2006,
47. J.T. Bonner, "Why Size Matters: From bacteria to Blue Whales", Princeton University Press, 2006.
48. J.W. Peterson and K.D. McWatters, "The measurement of upper-air density and temperature by two radar-tracked falling spheres", NASA CR-29, 1965.

(Received 9 November 2007; 23 November 2007)

* * *