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Solar Hot Air Balloons for Terrestrial and Planetary Atmospheres

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1 Introduction

Recent miniaturization trends permit scientific investigations using low cost and lightweight detection systems. For example, the Arduino-based Gem infrasound sensor/logger combination weighs just 70 grams but can detect ground explosions from as far as 330 km away (Anderson et al., 2018) and the University of Reading has developed a volcanic ash detector that attaches to a standard radiosonde (Nicoll and Harrison, 2010). One of the primary challenges of using these types of systems on balloon-borne platforms is the cost, technical difficulty, and operational risk of the flight system itself. While standard meteorological balloons are low cost, simple to use, and are virtually guaranteed to terminate after several hours via envelope burst, they cannot sustain a level altitude. Superpressure weather balloon concepts that vent gas or use tow balloons are complex and may be unreliable. Zero pressure and superpressure balloons are expensive and require a means of flight termination. In contrast, a passive solar powered hot air balloon is inexpensive, simple to manufacture (even by the researchers themselves), flies at a level altitude in the upper troposphere to lower stratosphere, and lands reliably after sunset. On the other hand, they have a low lift to size ratio and require clear, calm weather for a successful launch. For certain classes of payloads and institutions, however, they represent a very cost effective means of delivering scientific equipment to the stratosphere for multi hour level flight.

The first solar hot air balloon was constructed in the early 1970s (Besset, 2016). Over the following decades the Centre National d'Études Spatiales (CNES) developed the Montgolfiere Infrarouge (MIR) balloon, which flew on solar power during the day and infrared radiation from the Earth's surface at night (Pommerau and Rougeron, 2011). The balloons were capable of flying for over 60 days and apparently reached altitudes of 30 km at least once (Malaterre, 1993). Solar balloons were the subject of a Jet Propulsion Laboratory study that performed test flights on Earth (Jones and Wu, 1999) and discussed their mission potential for Mars, Jupiter, and Venus (Jones and Heun, 1997). The solar balloons were deployed from the ground and dropped from hot air balloons; some were altitude controlled by means of a remotely-commanded air valve at the top of the envelope.

More recently, solar balloons have been employed for infrasound studies in the lower stratosphere (see Table 1). The program began in 2015, when a prototype balloon reached an altitude of 22 kilometers before terminating just prior to float (Bowman et al., 2015). An infrasound sensor was successfully deployed on a solar balloon during the 2016 SISE/USIE experiment, in which an acoustic signal from a ground explosion was captured at a range of 330 km (Anderson et al., 2018; Young et al., 2018). This led to the launch of a 5-balloon infrasound network during the Heliotrope experiment (Bowman and Albert, 2018). The balloons were constructed by the researchers themselves at a materials of less than $50 per envelope.

2 Theory of Operation

A solar hot air balloon consists of an envelope made of material that absorbs sunlight. This heats the air inside, decreasing internal density enough to achieve positive buoyancy. A variety of configurations are documented in the extant literature, including cylindrical, natural, and tetrahedral designs; some have clear outer envelopes and internal absorptive surfaces. The design discussed here is the Sandia National Laboratories "Heliotrope" flight system. It consists of a spherical envelope constructed from 0.31 mil clear

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Campaign	Balloon	Payload kg	Launch Location	Launch Time UTC	Flight hours	Float Altitude m
UNC Test Flight	1[a]	0.8	Chapel Hill, North Carolina	5-29-2015 13:15	3.5	22100
USIE	1	1.8	Albuquerque, New Mexico	9-24-2016 14:30	13*	15500*
	2	1.8	Ft. Sumner, New Mexico	9-28-2016 15:57	10	16500*
Heliotrope	1	0.78	Socorro, New Mexico	6-25-2017 13:00	14.5	21700
	2	0.70	Socorro, New Mexico	6-25-2017 13:12	14.5	23900
	3	0.72	Socorro, New Mexico	6-25-2017 13:17	14.5	23900
	4	0.72	Socorro, New Mexico	6-25-2017 13:25	14.5	23000
	5	0.75	Socorro, New Mexico	6-25-2017 13:35	14.25	22000*
Arctic Test Flight	1	0.5*	Oliktok Point, Alaska	8-05-2017 02:00	6*	> 10000
	2	0.5*	Oliktok Point, Alaska	8-05-2017 03:30	6*	> 10000
Jon Magnus	1[b]	1.0*	Albuquerque, New Mexico	4-4-2018 14:30	3	-
Redvox	1[c]	0.4*	Albuquerque, New Mexico	4-10-2015 15:30	14	16000*

*Estimated value

[a]Flight terminated just before reaching float

[b]13 m envelope; flight terminated at 7500 m due to clear air turbulence

[c]4 m envelope

Table 1: Recent solar balloon campaigns.

high density polyethylene sheeting, typically available as "light duty painter's plastic" at hardware stores and online. The gores are typically sealed with heavy duty shipping tape, although thermal welding can be employed to save weight at the risk of a less durable envelope. Following this, the interior of the envelope is coated with air float charcoal powder, which clings to the plastic and absorbs sunlight. The bottom is left open (Figure 1). The total time to construct a 6 m envelope (capable of lifting about 2 kg) is 3.5 hours for a team of two, and the materials cost approximately $50.

Launch conditions must include sunlight and light winds, although balloons have been successfully deployed under moderate cirrus cover. Solar power typically reaches usable levels about a half hour after sunrise. A single person can inflate a Heliotrope by towing the envelope back and forth, although there is a limit to the amount of air that can be ingested. Fans are more effective – a team of two can launch a balloon every 5 or 10 minutes with this method (see the Heliotrope experiment in Table 1 and Figure 2). If the balloons can be preheated in a hangar, they can be launched in much windier conditions (e. g. the Arctic Test Flight shown in Table 1). Jet Propulsion Laboratory studies report successful solar balloon deployment by dropping them and allowing them to ram inflate; this is presently being investigated using meteorological balloons to tow the Heliotropes aloft.

A 6 m diameter Heliotrope balloon can deliver 800 grams to above 20 km altitude and 2 kg to about 15 km altitude. The balloon ascends slowly, typically less than 1 m/s after launch, rising to 2-3 m/s at the tropopause, and decreasing again thereafter. Regardless of payload mass, these balloons take about 3 hours to reach float. Once there, they oscillate up and down by 50 to 100 m over a period of several hundred seconds. The average float altitude may vary by several hundred meters over the course of the day, likely due to changes in sun angle and Earth albedo. The balloons descend at sunset, taking one to several hours to land. It is believed that the envelope stays inflated in some cases, but the wide variation in observed impact speeds (1 m/s for a 1.8 kg payload without a parachute, 6 m/s for a 0.7 kg payload with a parachute) indicates that descent can be unpredictable. For that reason, parachutes are recommended.

3 Terrestrial and Planetary Applications

The Heliotrope solar powered hot air balloon is cost effective, simple to make, and capable of lifting small payloads into the stratosphere during daylight hours. This and similar designs are ideal for gram to kilogram scale science packages that require up to ten hours of level flight at altitudes from 15-24 km, although higher elevations are certainly possible. Campaigns that require many balloons launched over days to weeks can benefit from the low cost and ease of construction of these balloons, particularly in regions with abundant sunlight. Indeed, the Heliotrope infrasound experiment described in Bowman and Albert (2018) would not have been possible had the solar flight system not been available. The prospect of multi day flight during perpetual sunlight in the Arctic/Antarctic summer is particularly attractive, and current activities

Figure 1: A Heliotrope just after launch, showing the darkened envelope, open bottom, scientific payload and tracker packages (white boxes), and parachute (orange).

Figure 2: Solar hot air balloons carrying infrasound sensors launched as part of the 2017 Heliotrope experiment.

are focused on testing this concept. Using solar balloons to lift radiosondes could cut down on the cost of shipping helium to remote locations even in the midlatitudes and tropics; solar or helium flight systems would be employed flexibly as the weather permits. Finally, the balloons' low cost and simplicity lend them to STEM outreach opportunities, perhaps as a sister program to the NASA High Altitude Student Platform (HASP).

Solar hot air balloons are a lightweight and low risk means of multi hour flight on planets such as Venus, Jupiter, and Mars. More complex designs, such as the CNES MIR balloon, may be able to sustain flight for weeks to months given the appropriate radiation conditions. Planets with low axial tilt, such as Jupiter and Venus, may have regions of perpetual sunlight in the atmosphere above the poles. A simple solar hot air flight system could remain aloft indefinitely provided the polar vortex was of sufficiently small radius.

Solar hot air balloons offer an attractive alternative to lift gas driven balloons for certain mission classes. The Balloon Program Office could further explore the prospects of this flight system by

- Utilizing them for low mass payloads that do not require night flight
- Further investigating designs that could operate on planets such as Jupiter or Venus
- Developing a STEM program that involves high school or undergraduate students building the balloon envelopes and payloads

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