CONCEPT NOTES FOR A LIGHTSAIL BALLOON

Michael Paine, 4 August 2014. Update August 2021

mpaine@tpg.com.com

Background

Lightsails are innovative propulsion systems for spacecraft that use mirror surfaces to reflect photons (usually of sunlight) and create a reaction force that can be used to control the motion of the spacecraft. A lightsail is similar in concept to a yacht with the sail aligned to create thrust in a useful direction. In the case of a lightsail orbital mechanics (i.e. gravity) takes the place of the reaction of the yacht hull in the water.

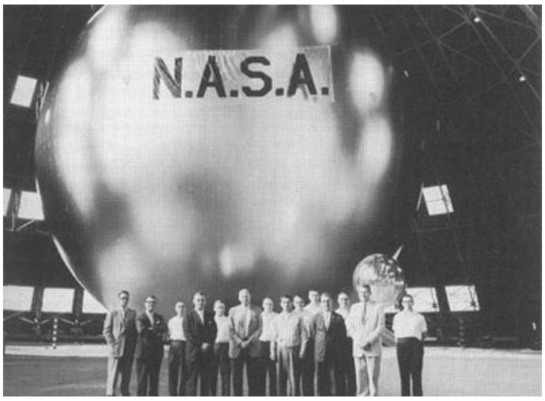
These notes set out an idea for a spacecraft that uses the lightsail concept but incorporates the lightsail component (mirrored surface) in a transparent balloon instead of a conventional standalone sail.

These notes are provided without patent or copyright to encourage engineering students to develop the concept further and to determine whether it is feasible for interplanetary spaceflight.

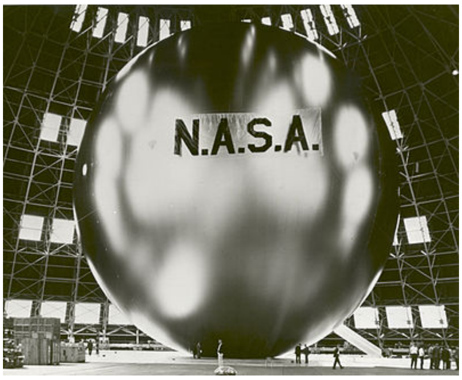
There are numerous resources available on the design and operation of lightsails. "Starsailing" by Lou Friedman (Wiley 1988 - paperback only) is an essential book for this purpose.

The idea of using a balloon to create the structure to hold the lightsail in place arose from listening to an episode of Planetary Radio (podcast, The Planetary Society) where methods of deploying conventional lightsails were being described. There are some ingenious designs for this but I wondered if there were other designs that also take advantage of the microgravity and the near vacuum of space. That made me think of a balloon.

At least two large balloons have been deployed in outer space: Echo 1 and Echo 2 (http://en.wikipedia.org/wiki/Echo_1). Echo 1 was a spherical balloon 30m in diameter with a silvery surface that reflected visible light. It was launched in 1960 and, surprisingly, stayed in orbit until 1968. Echo 2 was 41m in diameter. According to Wikipedia "its skin was rigidizable, and the balloon was capable of maintaining its shape without a constant internal pressure. This removed the requirement for a long term supply of inflation gas, and meant that the balloon could easily survive strikes from micrometeoroids." Echo 2 was launched in 1964 and stayed in orbit until 1969.



Echo 1 (NASA/Wikipedia)



Echo 2 (NASA/Wikipedia)

The balloon concept

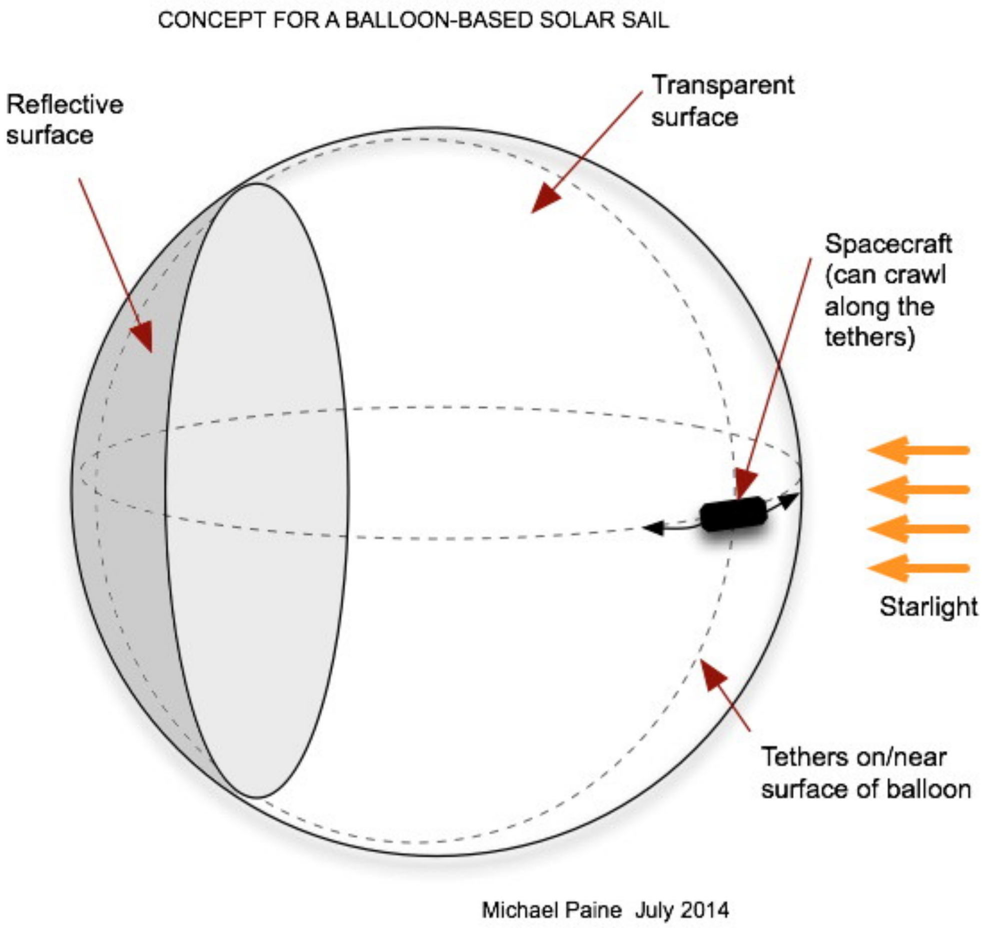
Two of the key functional requirements of a lightsail are that it holds its shape and that it can be steered so that the thrust is obtained in a desired direction. The nature of orbital mechanics means that the most useful direction is along the orbital path - speeding up the spacecraft to expand the orbit and slowing it down to shrink the orbit (see Friedman 1988 - Figure 2.1).

Clearly a fully reflective balloon like Echo 1 does not achieve this because the thrust is always parallel to the direction of sunlight. But what if only one third, or so, the of balloon is reflective and the rest is transparent to starlight? This would create a lightsail similar in shape to an umbrella - a shape that has been considered for use as a lightsail (Friedman 1988 - Figure 3.6).

A balloon should be relatively simple to deploy in space - as was done with Echo 1 in 1960. It can also be designed to hold its shape in the event of a meteoroid strike - like Echo 2.

One advantage of this concept is that it should be readily scalable. If it works for a 10m diameter balloon it should work for a 500m diameter one.

Next we need to work out a way to attach the spacecraft to the balloon so that it can steer the lightsail and is dynamically stable. One option is to run strong, lightweight tethers ("ropes") around the balloon and attached the spacecraft to these tethers using a mechanism that can crawl along the tethers - to re-position the spacecraft around the surface of the balloon. This is illustrated below.



The maximum thrust along the orbital path will be an orientation of 45 degrees to the orbital path, when orbiting the Sun. Steering is achieved by moving the relatively heavy spacecraft partway around the surface of the balloon. It does not need to move much to produce a large change in the angle of the mirror because the torques will align the lightsail so that the new centre of pressure vector (from sunlight reflecting off the mirror) passes through the centre of mass of the combined system (balloon and spacecraft). The spacecraft would need to be capable of travelling along, say, a 30 degree arc to move between maximum thrust (directly away from the starlight - but not a useful direction) and minimal thrust, with the "umbrella" edge on to the starlight. One reason for having the mirror diameter smaller than the balloon diameter is to minimise the edge-on profile.

Incidentally, due to the centre of pressure characteristics, the umbrella shape seems to make the whole system more sensitive to adjustment of the spacecraft position than with a flat mirror. With an umbrella it seems that the spacecraft will only need to move a few degrees around the balloon to go from maximum thrust to the optimum at 45 degrees to the orbital path. However it might be that this is too sensitive and is uncontrollable. If so, the spacecraft will need to be located further from the balloon.

Extended tethers would position the spacecraft so that it is well away from the surface of the balloon (not unlike a conventional hot-air balloon with the spacecraft replacing the basket). This could be on the concave or convex side of the mirror (which is more stable?). In the case of the convex side there would not be the energy loss from the starlight passing through the transparent portion of the balloon, if this loss is a problem.

A more radical option is to locate the spacecraft inside the balloon, but as indicated above, this could be a unstable configuration. And it would have other operational difficulties.

If the umbrella shape does result in unacceptable loss of efficiency or controllability problems, another option is to have a fully transparent balloon and attach a flat, disk shaped mirror inside the balloon. The balloon then serves to hold the disk in shape. In effect the mirror would be just the light grey portion of the diagram above. With this option the mirror diameter could equal the balloon diameter (effectively dividing the balloon in half) and so maximizing the mirror size.

Design challenges

There are several questions that need to be addressed about the concept:

a) Notwithstanding the Echo 1 and Echo 2 successes, will the deployment of the balloon and tethers be an issue?
b) What tethering options, if any result in a dynamically stable spaceflight?
c) Will tethering the spacecraft to, and moving it along, the surface of the balloon enable it to steer the mirror and will it be stable?
d) Will the combined mass of the balloon and the tethering/steering system be low enough to provide efficient propulsion? (see Chapter 3 of Friedman 1988)
e) How large should the reflective surface be, compared with the diameter of the balloon? In other words, how small should the edge-on profile be? Will a balloon much larger than the reflective portion result in other mission difficulties?
f) A curved mirror (umbrella shaped) is less efficient than a flat one for lightsail purposes so will this efficiency penalty be too great?
g) Should the risk of meteoroid collision be addressed, as with the Echo 2 satellite, or is the resulting mass penalty too great?
h) Can a suitable transparent balloon be made and does it also need to transmit at non-visible-light wavelengths to maximise propulsion efficiency? Will non-transparent wavelengths, or the solar wind, result in dynamic instability?
i) Will excessive heating in the interior of the balloon be a problem?
j) Will heating at the focal point of the reflector be a problem (although not a parabola, partial focussing is likely to occur)? Can this energy be used by the spacecraft (or is this a perpetual motion dilemma)?
k) Can the balloon be "deflated" and stowed when not needed?

Answering these questions, and others, should show whether the concept is feasible and deserves further research.

Study themes

There is a wide range of engineering topics involved in lightsail design, including:

- Orbital mechanics
- Propulsion systems
- Mechanics and dynamics
- Material properties
- Feasibility studies
- Aerodynamics and hydrodynamics applied to reflected light propulsion systems (photondynamics? lumendynamics?)

Update: August 2021

The idea of inflatable sails has been used before, on land & sea. Maybe this design has an application in space?

Thank you to Lou Friedman setting out the principles and practicalities of lightsailing in his project and professional work and for providing initial comments on this concept.

Michael Paine is a mechanical engineer based in Sydney Australia. He is a member of the Planetary Society and maintains associated web pages on planetary science (http://www.vdrsyd.com//planet/index.html).

He was a pioneering windsurfer sailor in Australia which taught him about steering with sails - from first principles and by getting very wet. His engineering thesis was on the hydrodynamics of surfboards.