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An aero-spacecraft for the far upper atmosphere supported by microwaves

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Abstract

We propose a new type of air/space craft, supported from below at altitudes $\sim$ 70 km by a 'radiometric' temperature-difference effect. From there it can perform communications relay, environmental monitoring, data telemetry and high-quality optical imaging. We show that an ultralight, mostly carbon-fiber "Lifter" is feasible using the radiometric force, an effect known since the 19th century, in combination with optimized properties of known carbon fiber materials. A powerful microwave beam illuminates the Lifter underside to provide the required temperature difference. Optimally, the full ambient atmospheric pressure can be delivered to one side of the Lifter area by heating it well above the ambient air at 200 K. Beam powers of $\sim$ MW can support masses of $\sim$ 100 kg. We verified the magnitude and pressure dependence of the effect on carbon fiber disks heated by microwaves in laboratory experiments. Numerical simulations suggest that carbon fiber craft of certain shapes can provide passive stability while riding a narrow microwave beam, and active stabilization is available through beam manipulation.

1. Introduction

Between 30 and $\sim$ 150 km altitude no aircraft or spacecraft can sustain flight. This huge volume, the mesosphere, has been studied in situ only by craft passing through. We propose a propulsion concept that can work at these altitudes, using ideas both old and new, combining physics from the 19th century [1–3] and materials from the 21st [4,5]. Although ideas have been advanced before for platforms fixed above one point on Earth, none has proved feasible [6].

Sustained solely by microwave energy beamed from the surface, this "Lifter" observation platform would hover above a fixed spot at altitudes $\sim$ 60–80 km, able to view the Earth spanning a $\sim$1500-km diameter area below. It would be far cheaper to launch and could stay on station indefinitely, compared to flying past at orbital velocity. (NOAA now spends $\sim$ $400 million for polar monitoring alone, sampling $\sim$ 5 min /h with

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orbiting satellites.) Unlike proposed hovering systems that rely on solar power—e.g., hyper-blimps and robot planes with thirty propellers—the Lifter does not use buoyancy or aerodynamic lift, would have few moving parts and a far higher range of operating altitudes. Rain would not absorb a microwave beam if its frequency does not lie in an absorption band. The ground-based power beaming station, using state-of-the-art microwave technology, can be made mobile and transportable, supporting this new kind of air/spacecraft anywhere. This promises aerospace capability of great scientific and commercial utility.

Two innovations make the Lifter possible: optimized radiometric forces exerted on a heated surface at low air pressures, and advanced, lightweight materials—principally carbon fiber and foam structures. These are notably strong [7] and can withstand high temperatures when heated by microwave beams. We tested this on carbon fiber mats, heating them to ~ 2000 K without visible damage when viewed under a microscope.

2. Basic design

The Lifter (Fig. 1) consists of a thick ‘sail’ with a hot, absorbing bottom surface, a cool reflecting top surface, and a payload mass hanging beneath. A low mass control system on top is shielded by the Lifter from the beam and from the heat of the bottom, microwave-absorbing carbon surface. The Lifter diameter is some tens of meters and the payload hangs about twice the diameter below the Lifter for stability. The Lifter itself is very light, a few hundred kilograms, ~ 90% payload. It is built very much like solar sails for space propulsion or parachutes—a large area but very low mass per square meter. Advanced materials make this practical. A carbon–carbon microtruss with areal density ~ 10 g/m^2 can easily sustain the operating temperatures of the Lifter bottom, ~ 1000 K [4,5]. Such material is supported by struts that define the framework. For example, ultralight, absorbing nanotube cloth [7] could provide tensile strength twenty times that of steel and endure high temperatures.

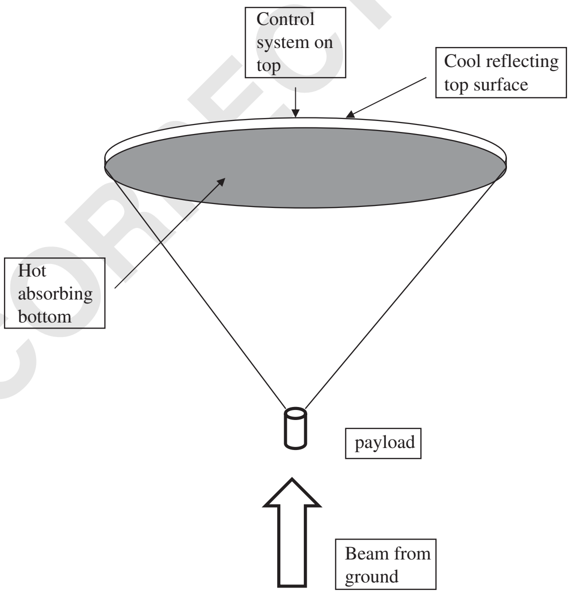

Fig. 1. The Lifter, a platform in the upper atmosphere supported by the radiometric effect, driven by heating the upper ‘sail’ by a microwave beam from the ground. Suspended payload is electromagnetically shielded from the beam from below. Its mass provides beam-riding stability.

Unlike any other aerospace system, most of the Lifter mass is in the payload hanging beneath the sail, shielded from the microwave beam. The Lifter rides the beam in a stable manner because of the payload mass hanging below, like a man beneath a parachute.

3. The radiometric effect applied to a carbon fiber platform

The Lifter is supported by the radiometric effect, familiar to the toy that has vanes spinning in a low-density air when heated on one side by sunlight. Radiometric forces were explored in the period 1873–1930, with little done since. By the 20th century we knew it primarily from the puzzling toy that spins opposite to the direction implied by the light pressure striking it. The physics is subtle; both Maxwell and Einstein [2,3] helped formulate the basic theory.

There are two effects acting. A *perimeter force* occurs because cool air molecules approaching an object at its edge are repelled both by hot molecules from the bottom surface, and by those cool molecules passing by from the cooler (upper) side within $\sim$ a distance $\sim L$ of the edge, where L is a mean collision-free path in air. The cooler molecules convey less momentum to the incoming molecules, which therefore strike the bottom surface more often, conveying more momentum toward the cool side. The perimeter force is proportional not to the entire Lifter area, but to the length of the heated boundary of the Lifter, and so the sum of many small areas about L wide. We envision the underside of the Lifter as made up of many carbon fibers, each roughly of length d, with d the Lifter diameter. Each fiber is $\sim L$ wide and they are separated by a distance $\sim L$. The effective acting area of N fibers is $\sim N\mathrm{d}L$ and the total fiber perimeter $\langle s\rangle \sim d^2/L$, which for our designs is 10^4 times the outer disk perimeter, d^2.

At pressures $p < 50$ m Torr, the perimeter force is directed from hot to cold, provided cooler air at temperature T_c can flow through, near or across the heated surface. In this range of p, the "perimeter" force is

$$F_s = (pL)\langle s\rangle(T_h/T_c - 1) \tag{1}$$

with $\langle s\rangle$ the total perimeter of all fibers and components. (We separate pL because it is constant as altitude h varies, $pL = 2.6\times10^{-3}$ N/m.) The crucial new idea is to make the perimeter much larger by using fibers in the Lifter underside.

There is also an *area force*. At lower pressures (higher altitudes) the area effect prevails

$$F_A = CpA(T_h/T_c - 1), \tag{2}$$

where A is the Lifter area, and C is a flow-pattern-dependent numerical constant ~ 1, but < 1.

The total radiometric force depends upon the temperature difference between hot and cold faces, $T_h - T_c$, the mean free path L of the air molecules, and on gas pressure p. It works only in the pressure range $\sim$ 10–100 mTorr, as is found in the high upper atmosphere, where mean free path L is on a millimeter to meter scale. As pressure p rises, our recent experiments [10] and earlier ones [1] show that the total force peaks at $p \sim 50$ mTorr, equivalent to an altitude $h = 75$ km. For a disk of 20 m diameter at altitude 80 km, $p = 1\,\mathrm{N/m^2}$, $T_h/T_c - 1 = 1$ and $C = 0.1$ yields $F_A = 31$ N. This can support 3 kg against gravity. By contrast, with $\langle s\rangle \sim d$, the craft diameter, $F_s \sim 0.2$ N. So for a planar sail, the area force is much larger than the perimeter force, unless the perimeter is increased. Which effect dominates depends upon air pressure and total perimeter length $\langle s\rangle$.

Around 50 mTorr the total radiometric force is

$$F_L = F_A + F_s = (pL)[\langle s\rangle + CA/L](T_h/T_c - 1). \tag{3}$$

We can improve lift capability by using both area and perimeter effects, so that $F_A \sim F_s$, by making $\langle s\rangle L \sim CA$. By using many fibers of length $\sim d$, we can achieve high $\langle s\rangle \sim d^2/L$, enhancing F_s. The optimum choice seems to be to place fibers about one mean free path L apart across the Lifter area A. Roughly, $F_L \sim (pA)(T_h/T_c - 1)$ at optimum.

Physically this means the full local atmospheric pressure can be delivered to the lower side of the Lifter area A by heating it well above the ambient $T_c = 200$ K.

4. Experimental trials

To check these ideas, we carried out experiments in a low-pressure metal-walled chamber, using 9.1 GHz microwaves striking carbon fiber disks. Under powers of $\sim$ kW, $T_h/T_c \sim 2$. Wall reflections compromised our simple disk lifting trials, so we mounted tilted disks on a rotating pivot. They rotated in the correct direction and at a rate verifying qualitative agreement with the force calculations above. This gives order-of-magnitude agreement that ~ 0.01 g can be supported by a Watt of microwaves when they are absorbed by the carbon fibers.

But disks of random fiber separation do not optimize the effect by increasing perimeter $\langle s \rangle$. We also checked the pressure dependence of the force, finding that rotation occurred between 10 mTorr. and 150 mTorr. This agrees with 19th and early 20th century experiments and theory [1]. Further, Knowles [8] has used optical light to lift solid carbon fiber disks, using only the area-effect force (i.e. no perimeter enhancement). He also found the lifting force to be ~ 0.01 g/W.

5. Design considerations

The total Lifter mass is the sum of the payload mass M_p and the other components, the absorber, top reflector and strut mass. The platform will always be lower in mass than the payload, as is also required for stability against perturbations, as shown by Abdhalla and colleagues [9,10].

Since the supported Lifter mass is proportional to $(T_h/T_c - 1)$, temperature is critical in Lifter feasibility. The best altitude is where the ambient temperature is lowest, $T_c \sim 200$ K, which luckily happens to be just in the pressure regime where the Lifter best operates, $\sim$ 70–80 km.

But what hot-to-cold temperature ratio T_h/T_c is practical? A Lifter heated from below reaches a temperature T determined by the incoming microwave power P balanced by cooling effects, so T scales with P. Cooling includes the conduction and convection of the air plus conduction through the Lifter body. The heating equation is

$$\mathrm{d}(kT)/\mathrm{d}t = P - KA_e(\mathrm{d}T/\mathrm{d}z) - (V/X)kT, \qquad (4)$$

where K is the thermal conductivity of the Lifter operating over an effective conducting area A_e. Generally, this second term will have contributions from both conduction through Lifter insulation and through the air filling any holes in a (honeycombed) insulating structure. The last term represents the heat loss through external air below the Lifter, operating over a scale height X. Here z is the vertical distance in the Lifter body and k the Boltzmann constant. The heated air thermal velocity V removes heat over the gradient scale X. We expect this term to be small compared with the loss of heat through the Lifter itself. Generally V is determined by a detailed air flow pattern between the hot bottom and cold top of the Lifter, and can be estimated as typically the thermal velocity of the hot underside air, at temperature T_h. We also neglect radiation as small, at the expected operating temperatures a few 100 K above ambient.

The second term can be written as $(K_a A_a + KA_e)\mathrm{d}T/\mathrm{d}z$ to show the additive terms from air convective cooling over a surface A_a and Lifter material cooling by conduction over surface area A_e. Here $K_a = 23.7$ J/(m s C) is the thermal conductivity of air (independent of density, and thus of altitude). We envision a honeycomb insulating structure between top and bottom, designed to maximize the temperature difference.

At steady state $\mathrm{d}T/\mathrm{d}t = 0$ and for temperatures $T_h < 2000$ K the air convection (last) term is small compared with the conduction (second) term. The temperature gradient $\mathrm{d}T/\mathrm{d}z$ we approximate as T/Z, with Z the Lifter height. The magnitude of Z is critical, for it tells how hot the Lifter can be. Probably Z of $\sim$ meter is plausible. The temperature of the hot underside is $T = T_c + ZP/(K_a A_a + KA_e)$, so the edge effect force becomes

$$\begin{aligned} F_s &= (pL)\langle s \rangle (ZP/(K_a A_a + KA_e)) \\ &= 2(pL)(P/T_c(K_a A_a + KA_e))T_c(Z/L). \end{aligned} \qquad (5)$$

The $(K_a A_a + KA_e)$ term can be engineered extensively lowering K to raise F_s.

Lightweight, low conductivity materials like carbon foam and carbon fiber mats have conductivities lower than air. Honeycombing the structure can further reduce conduction between Lifter bottom and top. A thin insulating vacuum layer between them might be optimal engineering to increase the temperature gradient and lower Lifter mass is the key to the concept.

We can write $A_e = fA$, with $f < 1$ and A the total Lifter area. A performance parameter for K can be written as $K = mK_a$, with m a numerical constant, expecting a good insulator will have $m \sim 1$. Then the denominator of the above equation is $K_a A[1 + f(m-1)]$ and we expect, through engineering, to make $1 + f(m-1)$ close to unity. Assuming this, at altitude

$h = 73.5$ km, the Lifter mass is roughly

$$M_L = 1150\,\text{kg}(P/10\,\text{MW})(Z/m). \tag{6}$$

We assumed a Lifter of diameter 20 m. If Lifter height $Z = 1$ m, the rough scaling is

$$\text{Mass supported/Power} = 115\,\text{kg/MW}. \tag{7}$$

Going to still lower altitudes can enhance this effect, but the basic radiometric physics begins to fail at higher pressures. A representative 73.5 km altitude means a pressure of 52 mTorr, and laboratory experiments show a falling off of the radiometric force at > 100 Torr. One can gain another factor of at most two by dropping lower in altitude h, to about 69 km. The optimum altitude depends on several competing effects, including choice of microwave wavelength. Optimum altitude is probably between 70 and 80 km.

6. Stability of the platform

Can a platform stably ride a narrow heating beam? Detailed calculations [9,10] show that lateral translation stability can occur if

- Lifter shape is conical concave toward the source, with interior top angle between 120 and 130°, so the top of the lifter is inclined 25–30° from the horizonal.
- Power beam spot size is about the same size as the diameter of the sail.
- Fall-off of power with angle ? to the vertical has a range of power indices between 2.5 and 4.0, i.e. Power $\sim \cos^{-2.5}\theta$ to $\cos^{-4}\theta$, with θ, the beam opening angle. Fortunately, typical values for microwave beams from a dish are within this range.
- Length of the connection between Lifter platform and payload, either a shaft or flexible lines, is about twice the Lifter diameter. From the first condition on this list, the connecting elements are about 4–5 times the Lifter height.
- Lifter does not experience a perturbation that drives it to pitch more than 45°to the vertical.
- Payload mass exceeds 95% of the Lifter mass. The ratio is like that of a parachute with a man as payload. Having a large payload ratio is attractive.
- Spinning the Lifter improves stability against toppling off the beam.

Stability simulations with a constant wind of magnitude between zero and local atmospheric pressure ($1\,\text{N/m}^2$) show that the Lifter is stable against transverse drift.

7. Constraints on the microwave beam

The Lifter is supported by energy beamed from a ground station that could be built today. Energy efficiency and the need to minimize the size of the radiating antenna determine the station size and emitted frequency. For example, for power beaming to be $> 70\%$ efficient, $Dd/h\lambda \geqslant 1.5$, where D is the transmitter antenna diameter, d the Lifter diameter, and h the altitude. At 95 GHz, $\lambda = 0.32$ cm. At a high altitude 80 km, dD must exceed $380\,\text{m}^2$ to get 70% transfer of energy. If we choose to make the Lifter sail large, say 20 m in diameter, then the transmitter antenna is 18-m diameter. Alternatively, a small antenna suitable for transport as a single dish 10 m in diameter would require a 38-m sail.

Megawatt average power microwave sources are now available, using gyrotron technology, and are used in fusion research. Single sources up to 5 MW average power exist up to the 200 GHz range. Dishes with mm scale accuracy have for decades given very high gains ~ 70 dB and are widely used in millimeter wave radio astronomy.

How can Lifter forces be optimized? Consider a Lifter made up of fibers spaced L apart and of length d, the Lifter diameter. To produce thrust from the edge effect of the incoming gas molecules must "see" a boundary, which means a fiber must be at least a mean free path wide. The edge effect occurs on both sides of the fiber. To optimize for greater thrust, the grid then has an optimum number of fibers, $N_f = d/L$. Each fiber gives a lifting effect on both sides, so the effective total perimeter of the grid is multiplied by 2. Then the total perimeter of the grid is, $\langle s\rangle = 2N_f d = 8A/\pi L$. With this optimum value of $\langle s\rangle$, we find $F_s = 8pA/\pi(T_h/T_c - 1)$, so for $T_h/T_c = 3$ we have about 5 times the net atmospheric force (pA) exerted on the underside of the Lifter. At $h = 80$ km pressure $p = 1\,\text{N/m}^2$, so a square meter supports about $2.5\,\text{kg}(T_h/T_c - 1)$.

To gain more force, we may go to lower altitudes, writing the Lifter mass per square meter supported against gravity as

$$M_L/A = 0.25\,\mathrm{kg/m^2}(T_h/T_c - 1)\exp(-x/6.67\,\mathrm{km}), \tag{8}$$

where x is the difference in altitude from our maximum 80 km, $x = h - 80$ km. This means that by dropping lower, for example to $h = 73.5$ km, $x = -6.5$ km $M_L/A = 0.66\,\mathrm{kg/m^2}$ $(T_h/T_c - 1)$. Note that using the above equation for s, $F_s = F_A 8/(\pi C)$, so since $C < 3$, F_s exceeds F_A.

We expect that for such optimized carbon fiber platforms the perimeter force will be several times larger than the area force, though this should be checked by experiment.

Generally, we can enhance the total lift by optimizing the perimeter effect, while keeping the area force F_A. Whether the two effects are additive depends on detailed design; optimization must be studied in the laboratory.

The perimeter effect enhancement is constrained by another major requirement, that the microwaves be absorbed, not transmitted, through the mesh of fibers. (Carbon fiber structures have been made with measured absorption of $\sim 99\%$; Knowles, private communication.) This constraint amounts to requiring the wavelength to be shorter than the fiber separation, $\lambda < b$.

To roughly scale the wavelength requirement, in the above case with $b = L = 2.6$ mm, making the spacing equal to wavelength, $\lambda < 2.6$ mm, corresponds to no transmission for frequency $f < 115$ GHz. Therefore, the power beam can use the transmission bands in the atmosphere at 94 and 35 GHz. In an actual Lifter we would likely use overlapping layers of fiber grid mats, so any microwaves passing through the first layer will be absorbed by the layers above it. Even higher frequencies may then be useful.

Is there an optimum altitude? Since, from the above equations, $F_L = F_A + F_s \sim (pL)[\langle s \rangle + CA/L]$, this requires trading off altitude against supporting thrust and frequency. Since pL is a constant but mean free path L increases exponentially with altitude, we can support more massive Lifters at modestly lower altitudes. Table 1 shows how some key Lifter system parameters scale.

The 73.5-km altitude corresponds to the "window" for microwave transmission at 35 GHz. Lower microwave frequencies propagate well. The next window is at 94 GHz, but atmospheric attenuation is higher there.

Table 1
Lifter parameters vs. altitude for heating ratio $T_h/T_c = 5$, Lifter diameter 20 m.

Altitude (km)	Atmospheric pressure ($\mathrm{N/m^2}$)	Mean free path L (mm)	Total Lifter mass (kg)	Minimum microwave frequency (GHz)
60	22	0.12	705	250
70	5.2	0.58	114	60
73.5	3	0.86	106	35
80	1	2.6	32	11.5
90	0.22	11.8	7.5	2.5

Altitude, mass and frequency can be adjusted to maximize lifting force.

Generally, for fibers of width w and separation b, the number of fibers in a diameter Lifter d is $N_f = d/(b+w)$, so the mass areal density is $w/4(1+b/w)$, where is the Lifter absorber density (perhaps of carbon fiber mesh). For carbon and $w = b$, this is $2.25\,\mathrm{g/m^2}$, well within the carbon fiber mat state of the art.

8. Conclusions

The Lifter provides a unique intersection of archival physics and advanced fabrication, to fashion a craft that differs greatly from all previous crafts—fundamentally, because propulsion remains on the ground. Lifters would be uniquely able to observe for distances out to about 750 km from their base beam. They would be practically invisible in the visible spectrum from such a distance, but luminous in the infrared at ~ 1000 K. At their extreme altitude, Lifters would be all but invulnerable to surface-to-air missiles and high-flying aircraft. The payload looking down could be transceivers for communications relay, intelligence gathering, environmental monitoring, data telemetry and high-quality optical imaging. It could measure local atmospheric conditions in this unstudied atmospheric region. In another type of application, the Lifter could serve as an adaptive optics beacon or an occulter (a "knife edge") for ground-based astronomy.

9. Uncited reference

[11].

Acknowledgements

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References

[1] L.B. Loeb, The Kinetic Theory of Gases, 3rd ed., Dover, New York, 1961, pp. 278–388, and references therein.

[2] J.C. Maxwell, Scientific Papers, vol. 2, p. 708.

[3] A. Einstein, Zeitschrift fur Physik 27 (1) (1924).

[4] M.S. Dresselhaus, G. Dresselhaus, P.C. Eklund, Science of Fullerines and Carbon Nanotubes, Academic Press, San Diego, 1996.

[5] R.I. Masel, Principles of Adsorption and Reaction on Solid Surfaces, Wiley, New York, 1996.

[6] J.D. Isaacs, A.C. Vine, H. Bradner, G.E. Bachus, Science 151 (1966) 682; J.D. Isaacs, A.C. Vine, H. Bradner, G.E. Bachus, Science 152 (1966) 800.

[7] A. Dalton, et al., Nature 423 (2003) 703.

[8] T.R. Knowles, Levitation of a Small Carbon by Visible Radiation, NASA/JPL/MSFC/UAH 12th Annual Advanced Space Propulsion Workshop, 2001. See also F. Meade, J. Nachmamkin, A Study of Radiometric Lift/Propulsion, ILIR Task Proposal, OLAC PL, Edwards AFB, 17 August 1992; F. Meade, G. Olson, Lightcraft LEO/GEO Concepts Study, AFRL-PR-Ed-TR-2001-0005, 2001.

[9] D. Georgiev, E. Schamiloglu, C.T. Abdallah, E. Chahine, AIP Proceedings, vol. 664, New York, 2003, p. 336.

[10] C.T. Abdallah, E. Chahine, D. Georgiev, E. Schamiloglu, AIP Proceedings, vol. 664, New York, 2003, p. 348.

[11] J. Benford, G. Benford, Microwave Sciences Report, January 2003.

Supporting Online Material

http://home.earthlink.net/~jbenford, Lifter Concept