Cryogenic Selective Surfaces—How Cold Can We Go?

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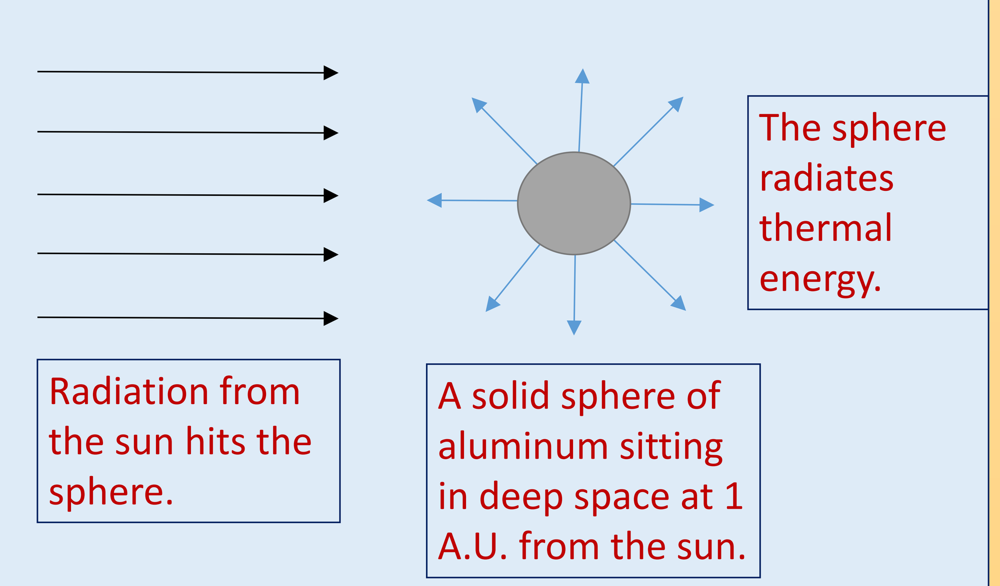
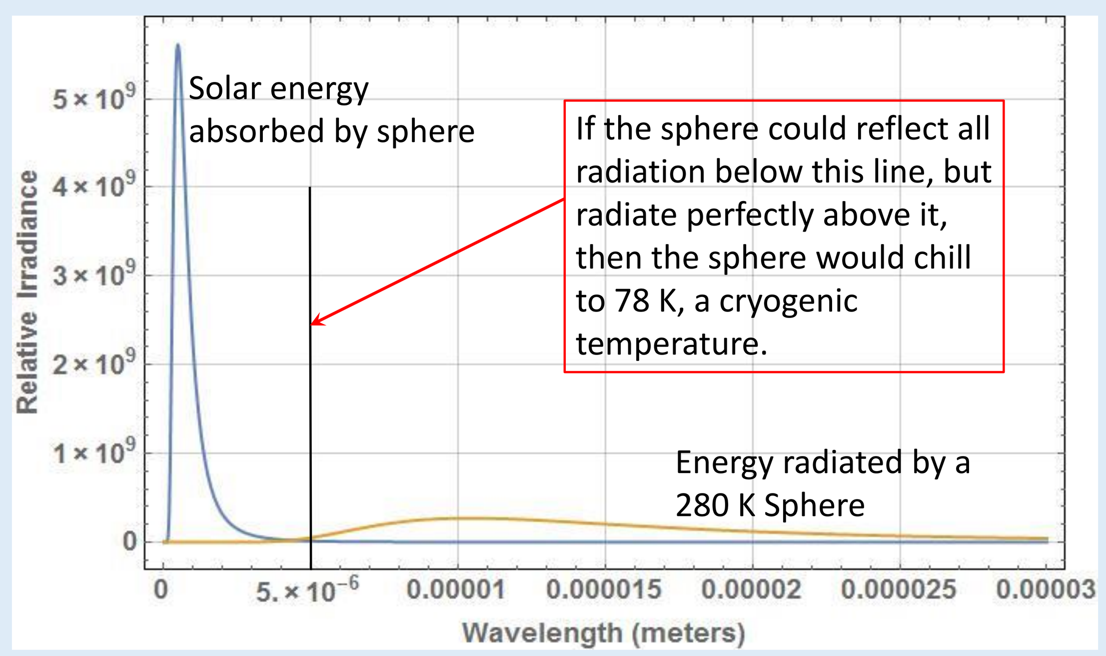
The Concept



Assuming constant emissivity the sphere will reach an equilibrium temperature of about 280 K (about 42 degrees F). The Earth on average is warmer than this due to greenhouse effects.



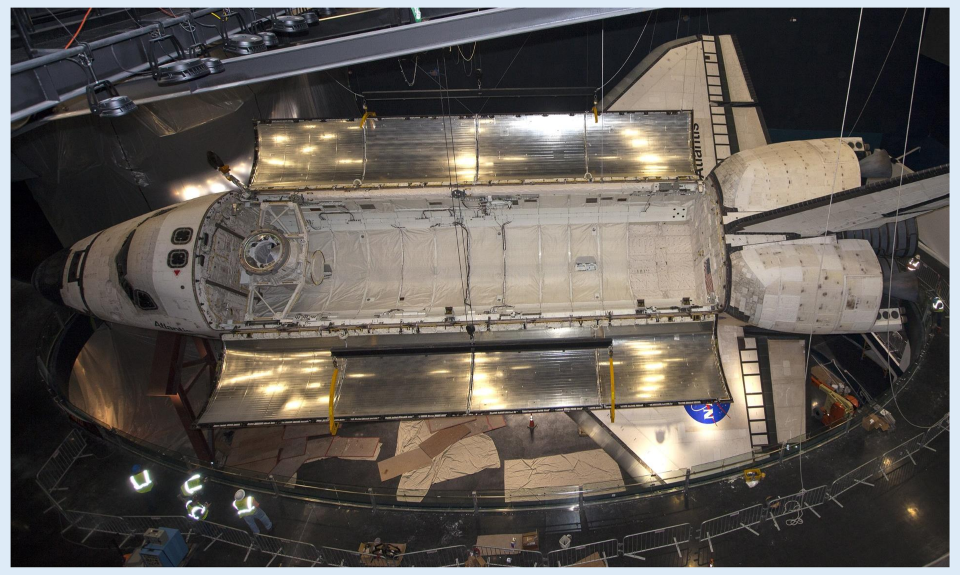
The area under the curves is equal (energy in equals energy out), but the sun's irradiance is at a much shorter wavelength than the irradiance produced by the sphere.

Surfaces designed to reflect one wavelength band and absorb the other are called **Selective Surfaces**.

Hibbard (1961) showed we could reach 40 K with ideal materials. But real world materials are not ideal. The key question is, Can we reach cryogenic temperatures with a realizable selective surface?

What Can we do with Them?

Selective Surfaces are already used in space applications, but not at cryogenic temperatures.

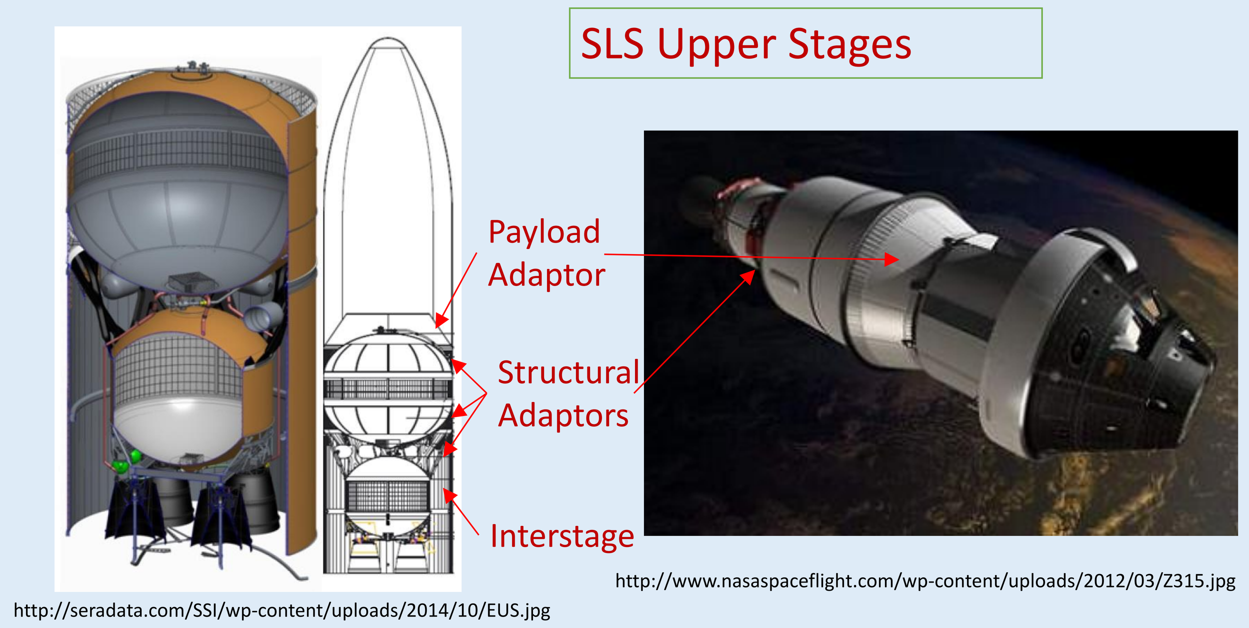


The Payload Bay doors of the Space Shuttle Orbiter were coated with a selective surface (aka thermal control coating) to allow heat rejection even in the presence of the sun.

Also, the Hubble Space Telescope used selective surfaces to reduce solar heating.

Can we maintain LOX on a trip to Mars?

SLS Upper Stages



The largest source of heat to LOX and LH2 tanks in orbit is conduction from warm attached structures (e.g. the stage adaptors and interstages). If a cryogenic selective surface could be put onto these external surfaces, lowering their temperature, then propellant boil-off could be substantially decreased (credit to Wesley Johnson at GRC).

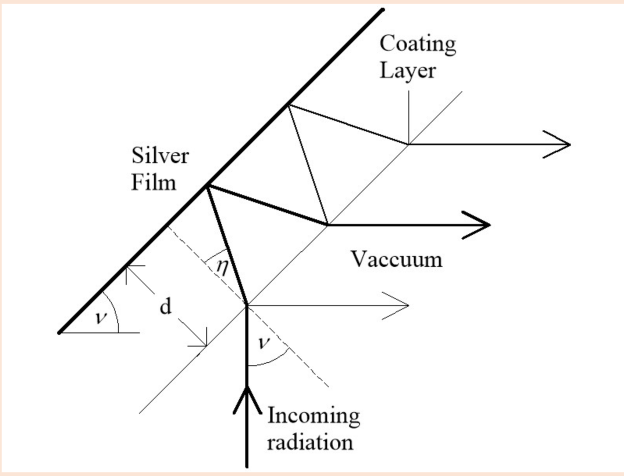
Can we achieve passive superconductivity?

Cryogenic selective surfaces might allow passive superconductors to operate in deep space enabling large scale energy storage and possibly active radiation protection.

First Try- Second Surface Mirrors

A common selective surface is a second surface mirror, where a material that is transparent in the visible, but dark in the far-IR is placed onto a mirror.

We modelled materials such as sapphire, CaF2, and MgF2 on silver.



We used complex forms of Fresnels' reflection equations, multi-pathing relationships, Plank blackbody emission integrals, and published data on the complex indices of refraction for both the transparent material and the silver. We did this for small flat elements, then mathematically constructed cylinders and spheres and equated solar power absorbed to power radiated (roughly 1 hour per structure on a Mac running Mathematica)

$$R_{SN}[\eta,\lambda]=\left[\frac{(n[\lambda]+i\kappa[\lambda])\cos[\eta]-(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}{(n[\lambda]+i\kappa[\lambda])\cos[\eta]+(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}\right]\left[\frac{(n[\lambda]+i\kappa[\lambda])\cos[\eta]-(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}{(n[\lambda]+i\kappa[\lambda])\cos[\eta]+(n_S[\lambda]+i\kappa_S[\lambda])\cos[\theta_S]}\right]^*$$

$$\boxed{A_P[\nu,\lambda]=\frac{T_P[\nu,\lambda](1-T_C[\nu,\lambda]^2R_{SP}[\eta,\lambda])}{1-T_C[\nu,\lambda]^2R_{SP}[\eta,\lambda]R_P[\nu,\lambda]}=\frac{(1-R_P[\nu,\lambda])(1-T_C[\nu,\lambda]^2R_{SP}[\eta,\lambda])}{1-T_C[\nu,\lambda]^2R_{SP}[\eta,\lambda]R_P[\nu,\lambda]}}$$

$$P[T]=2\pi\int_0^{\infty}\int_0^{\pi/2}\frac{2hc^2}{\lambda^5}\frac{A[\theta,\lambda]}{\exp[\frac{hc}{\lambda kT}]-1}\cos[\theta]\sin[\theta]\,d\theta\, d\lambda$$

Predicted Temperature Results

Coating Material	Coating Thickness*	2-Sided Plate** Temperature	Cylinder Temperature	Sphere Temperature
Sapphire	0.2 mm	195 K	172 K	161 K
CaF2	2 mm	183 K	165 K	156 K
MgF2	4 mm	183 K	163 K	153 K

*Optimal thickness **Plate facing the Sun.

Failure

Temperatures too high due to blue/UV absorption by silver.

Second Try- Dielectric Mirrors

Dielectric mirrors are multi-layer reflectors that have achieved better than 99% reflectivity over bands as large as 300-1100 nm. If we could extend this they might yield the solar reflectance needed to reach cryogenic temperatures.

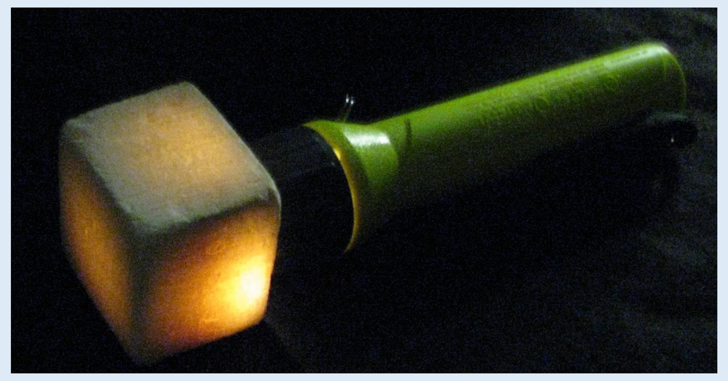
We contacted two coating labs: One admitted that they did not think a dielectric mirror could achieve our requirement (for $20K they could determine what might be possible) and the other proposed a mirror that clearly did not meet the requirement.

Likely Failure

Might succeed under substantial funding, but high risk of failure.

Third Try- Diffuse Scatterers-Solar White

A third possible cryogenic selective surface is composed of diffuse particles of a material like MgF2 or BaF2. Such a surface would appear white to most of the solar spectrum, i.e. "Solar White". The images below show the scattering and transmission of an object composed of pure glass fibers when exposed to visible radiation. Nearly all of the light is scattered out of the illumination face.



We modeled the performance of diffuse coatings composed of 0.25 micron diameter particles on top of silver, using a combination of radiation transfer theory, a Mie scattering model, and our second surface mirror analysis. The results, shown below, predict cryogenic temperatures!!!

Predicted Temperature Results

Coating Material	Coating Thickness*	2-Sided Plate** Temperature	Cylinder Temperature	Sphere Temperature
MgF2	6 mm	77 K	67 K	62 K
NaCl	6 mm	61 K	52 K	49 K
BaF2	5.5 mm	59 K	50 K	47 K

*Optimal thickness **Plate facing the Sun.

47 K!

Theoretical Success!

A Selective Surface that reaches Cryogenic Temperatures!
Now we can move on to applications.