Photonic components for space application

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Framework #1

- Space missions such as JUICE, and SOLAR ORBITER, will operate in very harsh environmental conditions;
- The degradation of optical components can lead to a misinterpretation of the scientific data due to an uncontrolled change of the instrument response;
- In a more dramatic scenario, the failure of a component can affect the operational capacity of the whole instrument.

- Thermal gradients
- Solar and planetary electromagnetic radiation
- Plasma (protons and alpha-particles)
  - Low energy particles
  - High energy particles and Gamma rays
- Particulates and contamination

Radiation testing of optical coatings for space

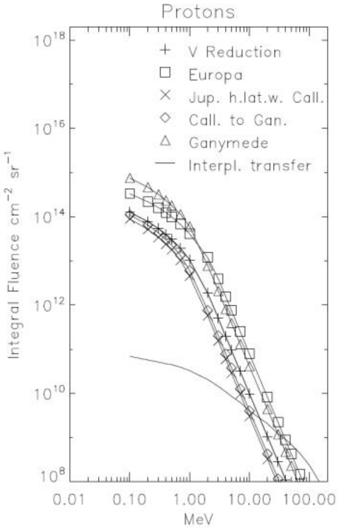
Simple coating samples										
Samples dimensions: 2.5 cm² diameter										
	Sample type	Structure	Parameters	Substrates	Ref	p	He+	e	Tot	# Deliv
1	S1W Au	single layer	240 nm adhesion: Cr	Si wafer	5	29	22	9	65	67
2	S1G Au	single layer	240 nm adhesion: Cr	Suprasil	5	5	2	9	21	23
3	S2W Al	single layer	200 nm adhesion: Cr	Si wafer	5	29	22	9	65	64
4	S2G Al	single layer	200 nm adhesion: Cr	Suprasil	5	7	4	9	25	25
5	S3GUV SiO_2	single layer	520 nm	Sapphire	5	29	22	9	65	63
6	S3W SiO_2	single layer	520 nm	Si wafer	5	13	10	9	37	36
7	S4G TiO_2	single layer	360 nm	Suprasil	5	29	22	9	65	67
8	S4W TiO_2	single layer	360 nm	Si wafer	5	13	10	9	37	38
9	S5G ZrO_2	single layer	340 nm	Suprasil	5	27	20	9	61	62
10	S5W ZrO_2	single layer	340 nm	Si wafer	5	10	7	9	31	31
11	S6W Al/SiO_2 Top layer: SiO_2	bi-layer	200/80 nm adhesion: Cr	Si wafer	5	15	13	9	42	42
12	S7W Ag/SiO_2 Top layer: SiO_2	bi-layer	210/80 nm adhesion: Cr	Si wafer	5	15	13	9	42	42
13	S8G SiO_2/TiO_2 Top layer: SiO_2	bi-layer	230/83.4 nm	Suprasil	5	15	13	9	42	43
14	S8W SiO_2/TiO_2 Top layer: SiO_2	bi-layer	230/83.4 nm	Si wafer	5	17	14	9	45	45
15	S9G SiO_2/ZrO_2 Top layer: SiO_2	bi-layer	230/104.2	Suprasil	5	15	13	9	42	42
16	S9W SiO_2/ZrO_2 Top layer: SiO_2	bi-layer	230/104.2	Si wafer	5	12	10	9	36	38
17	S10G Au/MgF_2 Top layer: MgF_2	bi-layer	200/80 nm adhesion: Cr	Suprasil	5	16	13	9	43	43
18	S10W Au/MgF_2 Top layer: MgF_2	bi-layer	200/80 nm adhesion: Cr	Si wafer	5	17	14	9	45	48
19	S11W Pt		220 nm adhesion: Cr	Si wafer	5	29	22	9	65	66
20	W			Si wafer	5	0	0	0	5	17
21	G			Suprasil	5	18	11	9	38	40

The European Space Agency (ESA) has funded the project Radiation testing of optical coating in space to systematically study the optical components performance degradation due to exposure to protons, alpha particles and electron: which include:

- Single layers
- Bi-layers
- Standard Materials used as substrates

Irradiation campaign

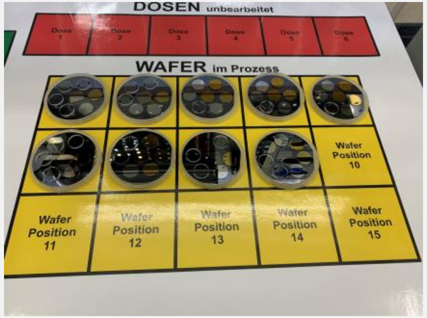
Fluence	Flux
$D_1 = 10^{12}$ [#/cm²]	$F_1 = 10^{10}$ [#/cm²·s]
$D_2 = 10^{13}$ [#/cm²]	$F_2 = 10^{11}$ [#/cm²·s]
$D_3 = 10^{14}$ [#/cm²]	$F_3 = 2 \cdot 10^{11}$ [#/cm²·s]
$D_4 = 10^{15}$ [#/cm²]	$F_4 = 5 \cdot 10^{11}$ [#/cm²·s]
$D_5 = 10^{16}$ [#/cm²]	$F_5 = 10^{12}$ [#/cm²·s]
$D_6 = 5 \cdot 10^{16}$ [#/cm²]	$F_6 = 2 \cdot 10^{12}$ [#/cm²·s]
$D_7 = 10^{17}$ [#/cm²]	$F_7 = 4 \cdot 10^{12}$ [#/cm²·s]



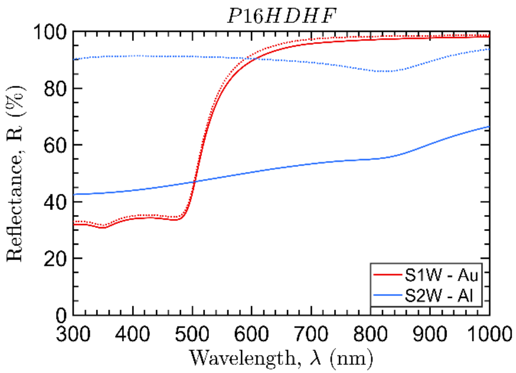
Increasing energy ↓

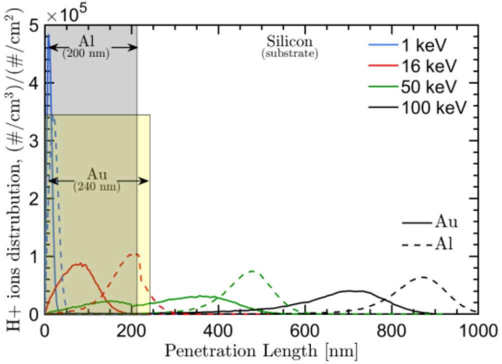
H+ ions														
Energy	Fluence							Flux						
	D_1	D_2	D_3	D_4	D_5	D_6	D_7	F_1	F_2	F_3	F_4	F_5	F_6	F_7
1 keV				X						X		X		X
					X					X		X		X
						X						X		X
16 keV				X						X		X		X
					X					X		X		X
						X						X		X
							X							X
50 keV			X						X		X			
				X					X		X		X	
					X						X		X	
100 keV		X							X					
			X						X					
				X					X					
1 MeV			X						X					
10 MeV	X							X						

Increasing fluence → Increasing flux →



Preliminary analysis

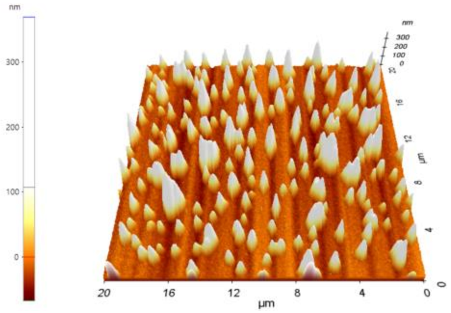




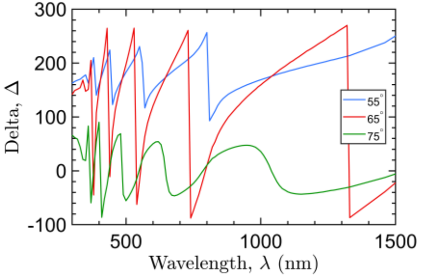
		Au	Al
Protons 1 KeV	P1LDLF	0,17	0,37
	P1LDMF	0,16	0,44
	P1LDHF	0,24	0,27
	P1MDLF	0,32	6,20
	P1MDMF	0,20	4,36
	P1MDHF	0,15	2,23
	P1HDMF	0,19	32,16
	P1HDHF	0,26	18,57
Protons 16 KeV	P16LDLF	0,13	0,27
	P16LDMF	0,22	0,23
	P16LDHF	0,18	0,24
	P16MDLF	0,24	4,05
	P16MDMF	0,10	2,77
	P16MDHF	0,08	3,36
	P16HDMF	1,19	41,30
	P16HDHF	1,38	38,63
	P16HHDHF	2,33	32,82
Protons 50 KeV	P50LDLF	0,08	0,14
	P50LDMF	0,10	0,35
	P50MDLF	0,13	0,35
	P50MDMF	0,15	0,35
	P50MDHF	0,09	0,30
	P50HDMF	0,37	0,38
	P50HDHF	0,23	0,23
Protons 100 KeV	P100LDLF	0,12	0,31
	P100MDLF	0,10	0,28
	P100HDLF	0,14	0,32
Protons 1 MeV	P1000HDLF	0,09	0,32
Protons 10 MeV	P10000HDLF	0,18	0,22

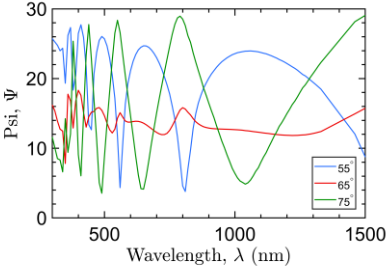
Non negligible damage

Negligible damage



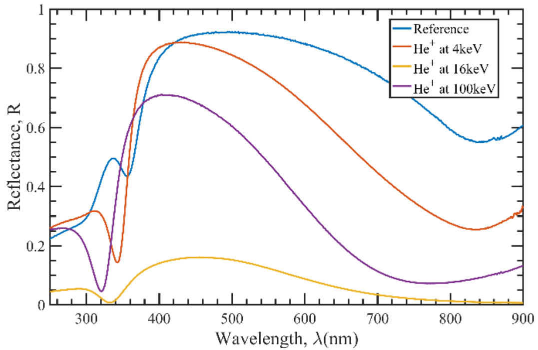
Other techniques:

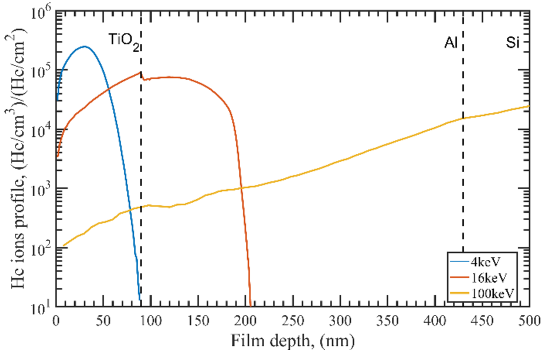


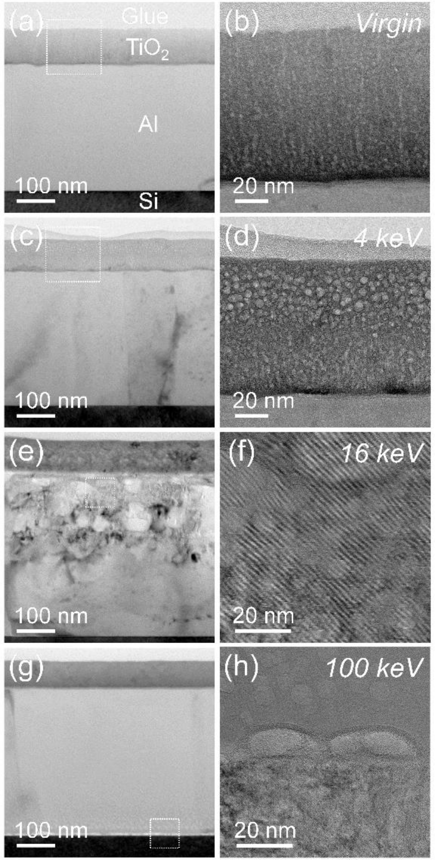


Protected mirror: example

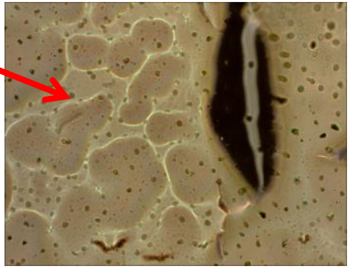
- Protected layer Al/TiO_2 irradiated with He+ ions at different energies



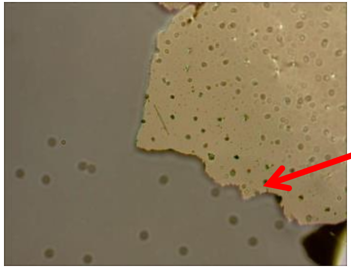




Blistered area



Delaminated area

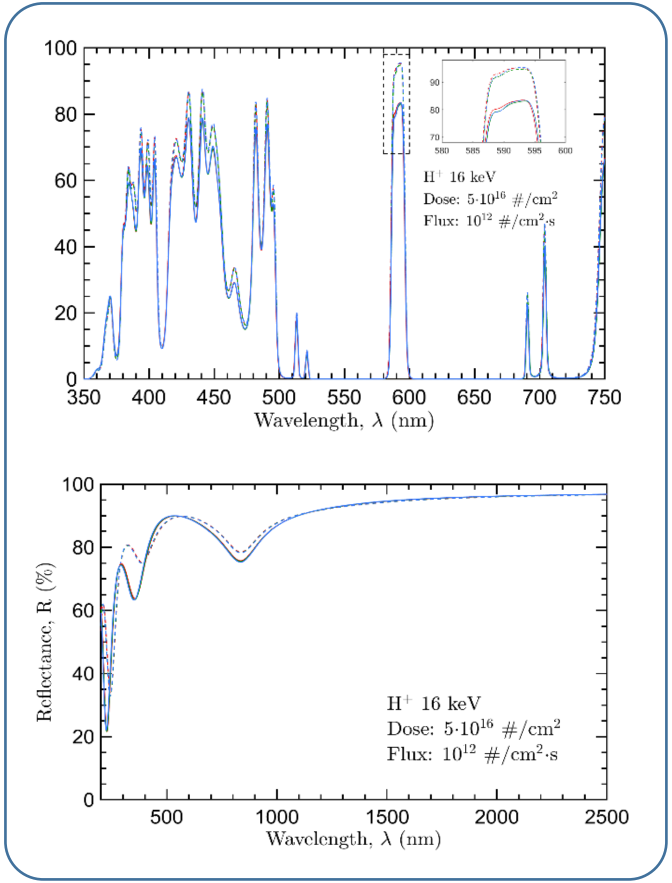


Flight representative coatings

	Sample type	Structure	Substrates	p	He+	e^-	ToT
1	C1Filter TiO_2/SiO_2	multilayer	Suprasil	6	6	3	60
2	C6G Al/SiO_2 Top layer: SiO_2	bi-layer	Suprasil	6	6	3	60

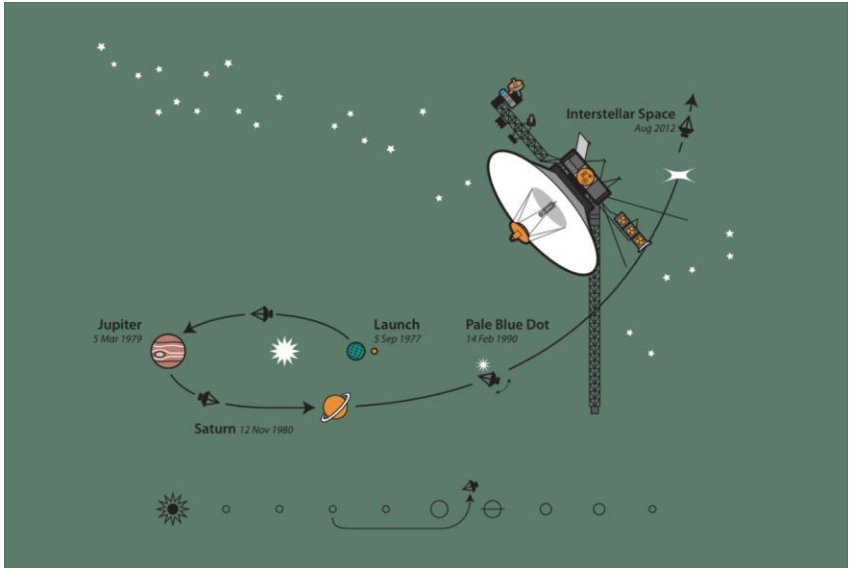
Label	Particle specie	Energy	Dose	Flux
P16HDMF	Protons	16 keV	5*10^16 #/cm^2	10^12#/cm^2/s
P100HDLF	Protons	100 keV	10^15 #/cm^2	10^11 #/cm^2/s
He16HDHF	He ions	16 keV	5*10^16 #/cm^2	4*10^12 #/cm^2/s
He100HDMF	He ions	100 keV	10^15 #/cm^2	5*10^12 #/cm^2/s
E10000LD	Electrons	10 MeV	35 Gy	-

		C1Filter	C6G
Protons	P16HDMF	8,64	4,42
	P100HDLF	1,27	0,47
He ions	He16HDHF	0,79	3,19
	He100HDMF	1,62	0,80
Electrons 10 MeV	E1000LD	0.66	0.07



Framework #2

Proposed by Kantrowitz in 1972, the idea of photonic propulsion is developing rapidly supported by an incredible technological improvement. The idea of interstellar explorations is not a dream any longer, but it requires a redefinition of the concepts of propulsion and spacecraft.

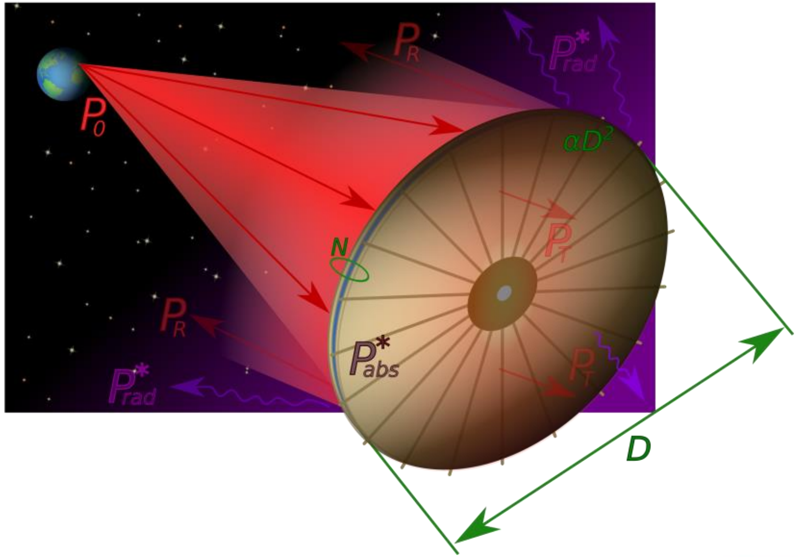


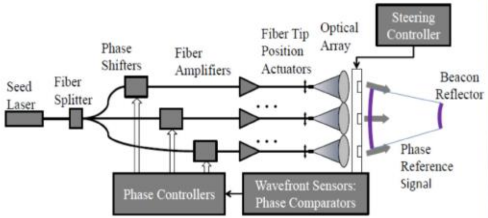
Example: Voyager 1

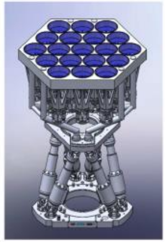
- launched in 1977
- left the solar system in 2012
- speed of 17 km/s (≈0.006%c)

⇒ Time needed to reach the nearest star is about 100.000 years!

The lightsail







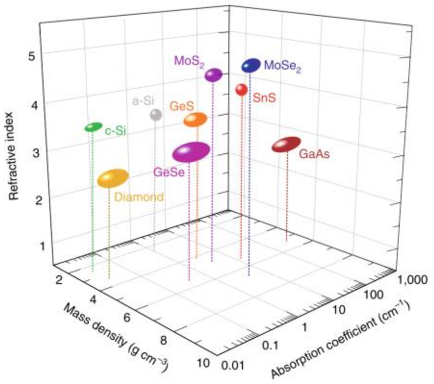
Starshot – Breakthrough Initiatives
Demonstrate proof of concept for ultra-fast light-driven nanocrafts, and lay the foundations for a first launch to Alpha Centauri within the next generation. Along the way, the project could generate important supplementary benefits to astronomy, including solar system exploration and detection of Earth-crossing asteroids.

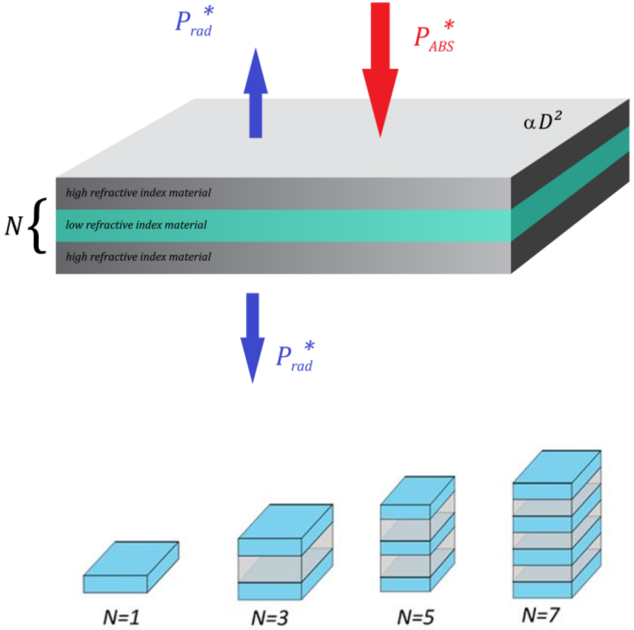
Requirements:
- Optimize the thrust in the Doppler shifted wavelength region of the laser source;
- Minimize absorption of laser radiation;
- Provide enough cooling power for thermal stability

The lightsail

Thin-film heterostructures could become multifunctional building-block elements of the light sail:

- Possibility to engineer the optical properties;
- substantial reflectivity while maintaining low absorption in the near-infrared;
- significant emissivity in the midinfrared, and a very low mass.





OPTIMIZATION:

Optimization of the lightsail requires the correct determination of the equation of motion of the object under the trust provided by the laser beam:

$$dt = \frac{mc^2\gamma^3}{P_0}\frac{1+\beta}{1-\beta}\frac{1}{A(\lambda,\beta)+2R(\lambda,\beta)}d\beta$$

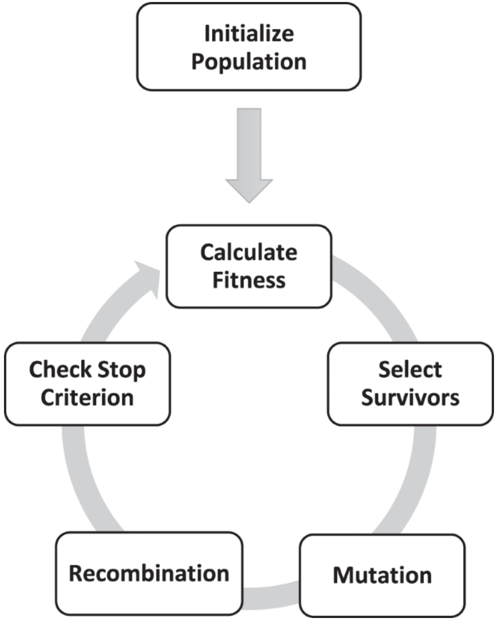
$$L(\beta_f) = \int_0^{t_f}\beta dt = \frac{mc^2}{P_0}\int_0^{\beta_f}\frac{\gamma\beta}{(1-\beta)^2}\frac{1}{A(\beta)+2R(\beta)}d\beta$$

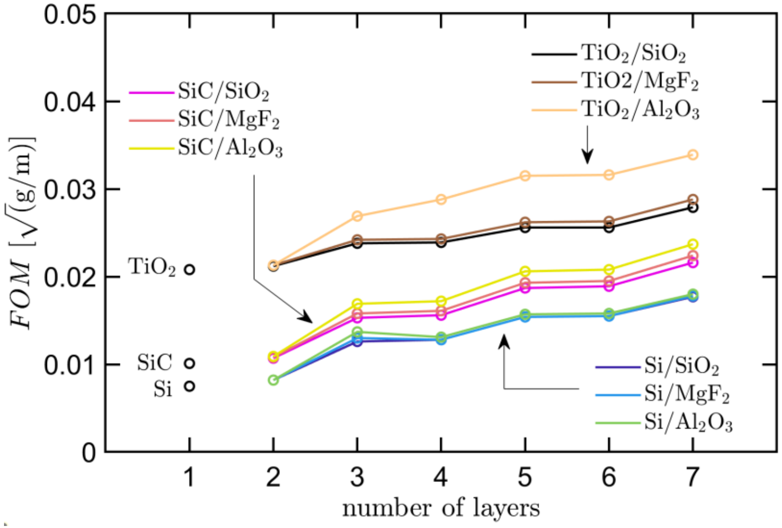
$$t(\beta_f) = \int_0^{t_f}dt = \frac{2\rho_s c^2}{I_0}\int_0^{\beta_f}\frac{\gamma}{(1-\beta)^2}\frac{1}{A(\beta)+2R(\beta)}d\beta$$

$$P_0 d_0 = 4\lambda_0 c^3\sqrt{m_p}\sqrt{\alpha}\int_{\mathbf{0}}^{\boldsymbol{\beta_f}}\frac{\boldsymbol{\rho_s}}{\boldsymbol{A(\beta)+2R(\beta)}}\frac{\boldsymbol{\gamma\beta}}{\boldsymbol{(1-\beta)^2}}\boldsymbol{d\beta} = 4\lambda_0 c^3\sqrt{m_p}\sqrt{\alpha}\cdot\boldsymbol{W}[\boldsymbol{x}]$$

Results - FOM

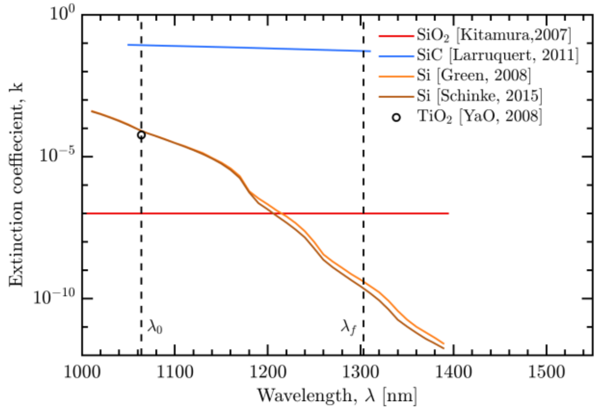
A genetic algorithm identifies the best-performing structures among a population that evolves while random mutations are applied to the thickness of the layers.





Results – Thermal evolution

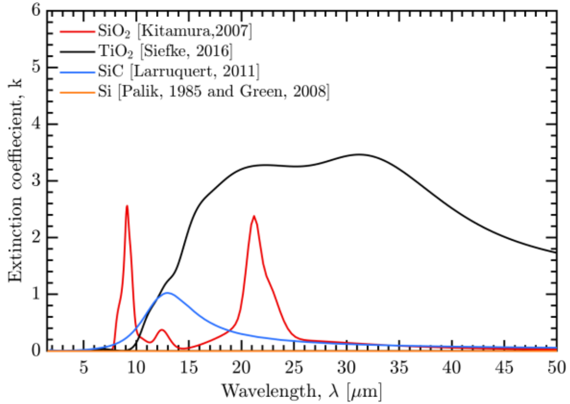
The lightsail thermal analysis of the sail is of upmost importance to understand whether the chosen structure will survive the acceleration process



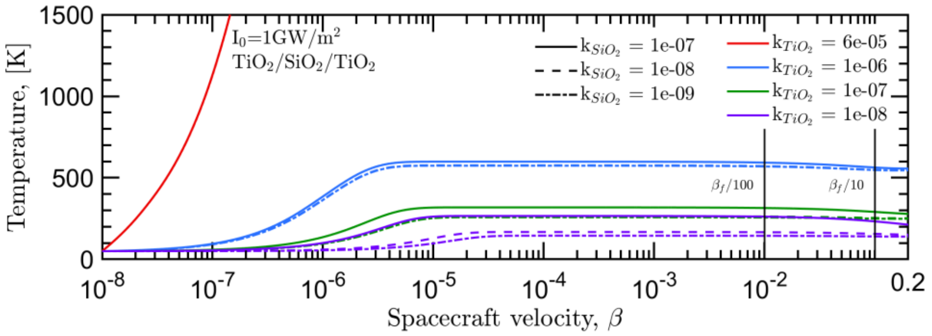
$$P^*_{abs} = P_0 \frac{1-\beta}{1+\beta} A(\lambda_0, \beta) \qquad P^*_{rad} = S \int \varepsilon_\lambda (T, \lambda) E_{b,\lambda}(T, \lambda) d\lambda$$

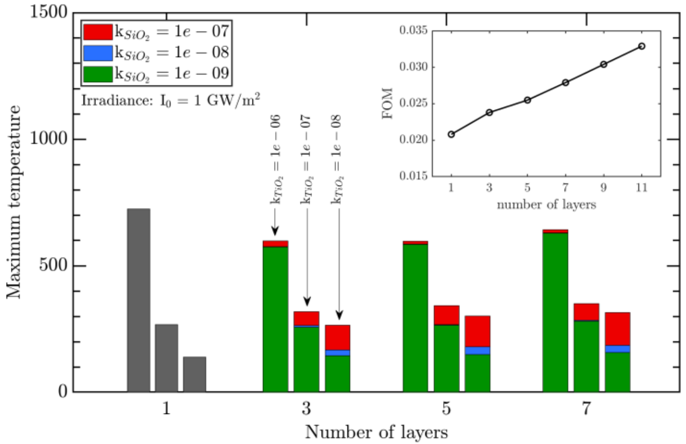
$$\frac{\partial T^*}{\partial t^*} = \frac{P^*_{abs} - P^*_{rad}}{C_{sail}}$$

$$\partial t^* = \frac{2\rho_s c^2 \gamma}{I_0} \left[\frac{1+\beta}{1-\beta} \frac{\gamma}{A(\lambda_0,\beta) + 2R(\lambda_0,\beta)} - \beta \int_0^\beta \frac{\gamma(\beta)}{(1-y)^2} \frac{1}{A(\lambda_0,\beta) + 2R(\lambda_0,\beta)} \right] \partial\beta$$



Results – Thermal evolution



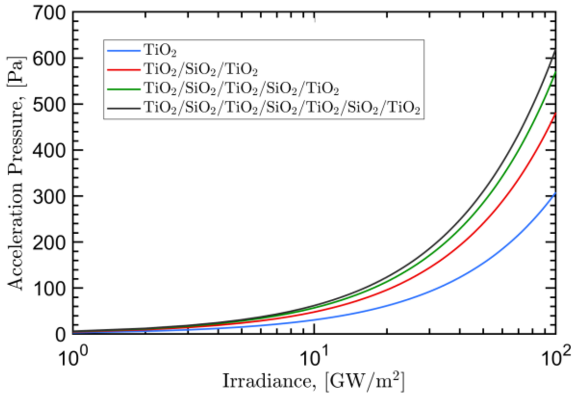


Acceleration pressure:

$$p = \frac{F}{S} = \frac{I_0}{c}\frac{1-\beta}{1+\beta}\left[(1+\beta)A(\beta) + 2R(\beta)\right]$$

Maximum sustained pressure:

$$p < (\sigma_{uts} \cdot t)/D$$



Thanks for the attention

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