SAILING TO THE STARS WITH PHOTONICS

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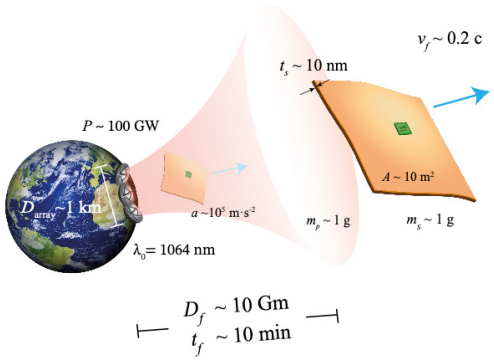


https://doi.org/10.1051/photon/202513460

Probing nearby star systems would take thousands of years for today's spacecrafts due to the immense distances between us and our stellar neighbours. In recent years, lightsails have gained interest as physically realistic interstellar vehicles. Lightsails are envisaged to be thin, highly reflective and lightweight membranes accelerated by high-power lasers up to substantial fractions of the speed of light. This ambitious endeavour entails substantial challenges, the solutions of which are rooted in photonics.

About 4.2 light years away, our nearest stellar neighbour, Proxima Centauri, harbours a planet in an orbit compatible with the existence of liquid water. Could it be home to life? From our own solar system, we can only gather indirect evidence that often raises more questions than it answers. Sending an exploratory probe would only make sense if it could send information back within one or perhaps a few human lifetimes. This would require speeds exceeding 10% of the speed of light, which simply cannot be attained by standard rocketry or by any spacecraft that carries its own source of energy and reactive mass. To reach relativistic speeds, an external source of momentum is needed.

From the beginning of electrodynamical theory, light was predicted to carry momentum, which could be transferred to matter upon absorption or reflection. The magnitude of this radiation pressure is small for everyday light intensities, and it is only with the advent of lasers and their extreme intensities that the effect could be exploited for applications on small length scales like optical tweezers and in fields of study like cavity optomechanics. On a larger scale, solar sails composed of highly reflective thin films can take advantage of the freely available light from the sun and its associated momentum. While its intensity at realistic distances is modest compared to lasers, the small radiation pressure can accumulate over long times to provide attitude and orbit control within the solar system. Several solar sail demonstrations have been successful, with a growing presence in the space community as a cheaper alternative for interplanetary exploration.

To go further, beyond our own solar system, the sun's intensity provides insufficient acceleration. The idea of *lightsails*, in contrast to solar sails, is that propulsion is provided by lasers with much higher intensities than that of the sun, enabling relativistic speeds. While first proposals became literally the work of science fiction [1], recent technological progress and "Moore's law" for lasers are bringing lightsails and interstellar exploration within reach.

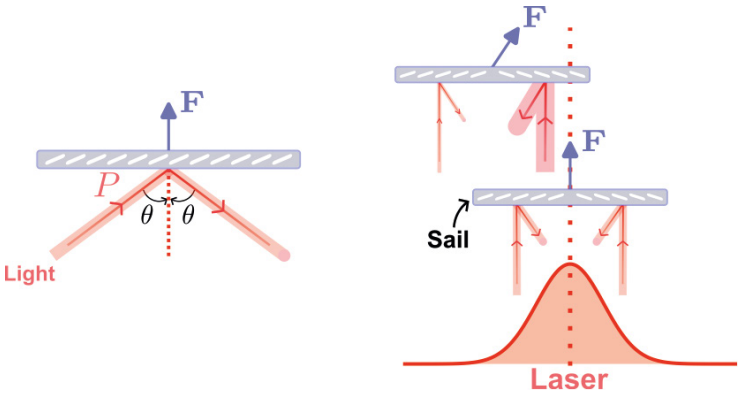
Every aspect of an interstellar lightsail mission represents an extreme engineering challenge, but all are possible within known laws of physics [2]. Project designs envisage an extremely low mass sail (10 m² in area but less than 10 grams total), carrying a chip-like payload containing

imaging or spectroscopic equipment and a communication laser [3]. A massive, kilometre-sized Earth-based laser array with a mind-boggling 100 GW of power accelerates the sail to 20% of the speed of light over ten or so minutes (see abstract graphic). The lightsail then cruises to Proxima Centauri over 20 years, takes a few pictures of its exoplanet and sends them back to Earth one photon at a time. It may sound farfetched, but an increasing number of scientists believe the many challenges of this mission can be overcome over the next several decades.

SENDING AND RECEIVING: THE LASER AND COMMUNICATIONS

The primary obstacle to the mission is the laser array, with the main concern being not only its power, but its size: the laser must be capable of focusing onto the small sail area until it reaches its target velocity. The sail acceleration, limited by material strength, leads to a predicted acceleration distance of order 10^{10} m, almost 10% of the distance to the Sun, while the laws of diffraction impose a laser-aperture diameter on Earth of order one kilometre. The entire array must be coherent with phase control to compensate for atmospheric turbulence and be able to compensate for the rotation of the Earth. Researchers have proposed hierarchical modular fibre-laser arrays, which work with internal phase sensing, or could be adapted with orbiting lasers for a coherent phase reference compensating the atmospheric fluctuations. To minimise atmospheric absorption, the laser wavelength is proposed to be in the near-infrared (NIR, *e.g.* 1064 nm—1550 nm). With current fibre-laser technology, the cost of such a laser would exceed one trillion ● ● ●

The fundamental principle enabling solar sails and lightsails is radiation pressure. Light incident upon a perfectly reflecting mirror at an angle θ experiences a radiation pressure force $F = 2P\cos^2\theta\hat{n}/c$, where P is the power intercepted by the mirror and $\hat{n}$ is the normal to the mirror surface. This equation holds in the ray-optics regime, where the characteristic size of features on the sail is much larger than the light wavelength. For more general scattering, wave optics can be applied to calculate the radiation pressure force. This often applies to sail structures, such as metasurfaces, that scatter light non-specularly, i.e. with components transverse to the incident light propagation. Transverse scattering is necessary for lightsails to remain centred within a propelling laser beam, maximizing propulsion and ensuring accurate transport to the sail destination. Indeed, the sail's scattering profile and laser beam's intensity profile can be designed in tandem such that small displacements from the beam's propagation axis change the proportion of power intercepted on sections of the sail [4]. This affects the light scattering in the transverse plane, enabling the sail to restore itself to the beam centre.



dollars. However, "Moore's law for lasers" predicts the same power laser would be up to three orders of magnitude cheaper within thirty years, becoming comparable to the budget of other large-scale science projects. Solar-cell farms can now fill areas in excess of one square kilometre – could phase-controlled, coherent, large-surface photonic crystal semiconductor lasers one day do the same [5]?

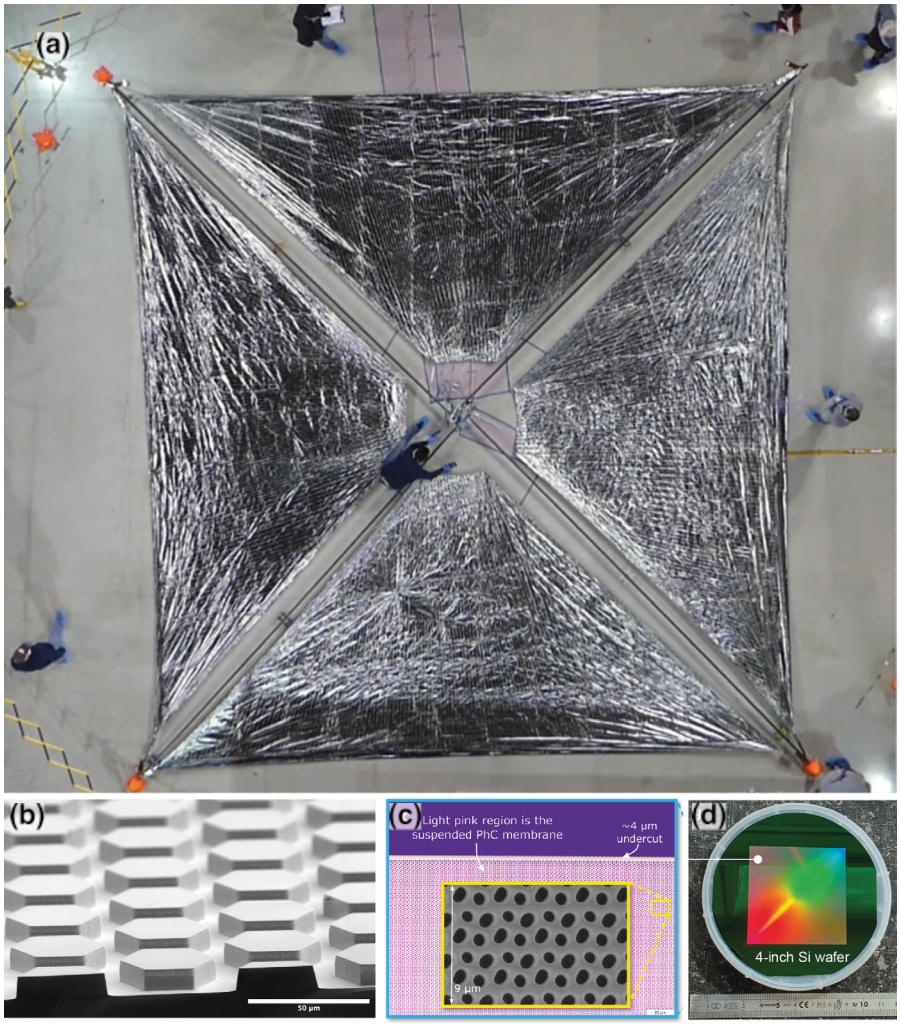
Once the sail reaches Alpha Centauri, it must send data back to Earth. The best bet is using an onboard laser, ideally repurposing the sail itself as a reflective mirror and using the immense aperture of the Earth-based accelerating laser as a detector. Powering the transmitter, pointing its beam towards Earth and isolating transmitter photons from those of the vastly brighter Proxima Centauri in proximity will be very challenging. No concrete engineering solutions have been proposed yet, but estimates of photon counts and possible modulation schemes have been analysed. Again, no laws of physics need to be violated, but this area will need much further study.

SAIL DESIGN AND MATERIAL SELECTION

If the sheer scale of the laser seems daunting, the constraints on the sail make it at least equally challenging: the sail must be extremely light, highly reflective, capable of withstanding tremendous accelerations in excess of 10,000g, and must remain taut and stable within the beam. All while surviving irradiation by the 100 GW laser beam.

To avoid overheating, the sail must be minimally absorptive at NIR wavelengths, where the laser is likely to operate, which precludes any metallic reflective coatings commonly used in solar sails, instead favouring dielectric reflectors [6]. Bragg reflectors come to mind as highly reflective dielectric-only structures, but the reflectivity benefit of additional layers is rapidly offset by the mass they add. Instead, single-layer, thin, high-index dielectrics are often optimal in terms of acceleration. Photonic crystals and metasurfaces have emerged as better solutions to optimise acceleration: properly designed photonic crystals based on arrays of holes have lower mass than dielectric slabs (e.g. Figure 1c), all while having increased reflectivity. In addition, non-specular reflections from photonic crystals, and phase shift from metasurfaces, can provide transverse forces needed for stabilising the sail in the beam (see below and the insert). An important design aspect to consider when designing the photonic properties of sails is that, for a 0.2c mission, the laser wavelength shifts by up to 22% due to the Doppler effect. Photonic

Figure 1. Experimental lightsail structures. (a) NASA's Advanced Composite Solar Sail System, a solar sail launched in 2024. The size of the sail is roughly that envisioned for a laser-driven mission. Reproduced from [https://www.nasa.gov/smallspacecraft/what-is-acs3/]. Copyright 2024 NASA. (b) Scanning electron micrograph (SEM) of a hexagonally corrugated lattice trilayer (Al_2O_3-MoS_2-Al_2O_3, scale bar 50 micron), a highly reflective lightsail candidate. Image kindly provided by M. Campbell as part of the work [M. Campbell *et al.*, arXiv:2508.05035 (2025)]. (c) SEM of a pentagonal-lattice photonic crystal with numerically optimized hole shapes. The entire fabricated structure is 60 mm × 60 mm. Adapted from [7] under a CC BY 4.0 licence. Copyright 2025 Springer Nature. (d) Fabricated Si3N4 circular-hole photonic crystal on a Si wafer, possessing enhanced broadband reflection. Adapted from [J. Chang *et al.*, Nano Lett. **24**, 6689–6695 (2024)] under a CC BY 4.0 licence. Copyright 2024 American Chemical Society.



solutions must thus be relatively broad band. Greater than 50% reflectivity averaged over the full Doppler band has been demonstrated in the lab on fabricated Al_2O_3-MoS_2-Al_2O_3 photonic crystals that are less than 200-nm-thick (Figure 1b), while other groups have developed membranes as large as 60 mm × 60 mm [7] (Figure 1c), a substantial step towards metre-scale lightsails.

Even minimal absorption in the sail leads to heating, which must be re-radiated into the vacuum of space, requiring high emissivity at mid-infrared (MIR) wavelengths. Materials like silicon that have high refractive index, and thus strong reflection, can be marred by excessive absorption without providing sufficient emissivity in the MIR. To prevent the temperature reaching material limits, the simplest solution is to add a highly MIR-emissive layer such as silica on the space-facing side. An even more promising strategy for simultaneous propulsion and thermal regulation comes from nanopatterning. Photonic crystals can be patterned at the NIR length scale, achieving high reflectivity, but further structured at the larger MIR length scale to resonantly enhance the sail emissivity. Alternatively, more advanced active photonic cooling mechanisms have been proposed, such as rare-earth-ion doping in the sail as used in solid state laser cooling. The most likely sail material candidates are thus dielectrics with high tensile strength to withstand the acceleration, high refractive index, low NIR absorption and crucially, the ability to be manufactured as large scale patterned freestanding films.

An area that requires more investigation is the sail's spatial temperature distribution and evolution. Dust particles are anticipated to be a significant source of heating, both from impact on the sail and, if they attach to the membrane, as a localised absorption site. Strategies to mitigate dust impacts (e.g. through detaching locally heated segments or shielding) are needed. In comprehensive thermodynamic simulations of sail-temperature evolution, a silicon nitride sail was shown to be effective at staying below its melting point over the full extent of the simulation, however, the simulation time was limited to just a few seconds due to computational costs (in comparison to the several-minutes-long acceleration phase).

STABILITY DESIGN

One of the biggest challenges with the lightsail mission is the sail's dynamical stability. The sail should intercept as much beam power as possible and stay on course to its target, so it must be confined within the laser beam for the entire acceleration phase lasting several minutes. Stability is nontrivial given continuous perturbations from, for example, atmospheric beam distortions or laser noise. There is no mass budget available for traditional stabilisers like thrusters, and the round-trip time of photons back to the laser is too long for closed-loop stabilisation. Stabilisation must thus be achieved locally on the sail, and be passive, ideally stemming from the radiation-pressure profile itself [2].

In essence, two mechanisms are required: restoring forces/torques and damping forces/torques. The restoring forces and torques trap the sail within the laser beam area, whereas damping forces and torques diminish the amplitudes of oscillations excited by perturbations. Passively generating restoring and damping can be done using the incoming laser momentum. However, this presents an inherent trade-off: laser momentum that is otherwise reflected specularly, thus providing maximum propulsion, must be partly scattered perpendicularly to the beam propagation to create transverse forces and torques (see the insert).

Restoring forces act like a spring, growing in magnitude with the distance between the sail centre and the laser-beam axis, guiding the sail back to the beam centre. In practice, this would be achieved by the sail scattering light in the same direction as the displacement from the laser-beam axis, thus repositioning towards the beam centre by conservation of momentum [4]. Restoring torques are similar, relying on changes in scattering with changes in angle relative to the ideal orientation. The simplest designs that exhibit such restoring properties are • • •

geometrically shaped mirrors, such as an inverted cone flying apex-down in a parabolic-intensity beam. Yet, photonic crystals and metasurfaces have emerged as superior candidates with restoring mechanisms because they can provide stability with a planar geometry (having better beam interception efficiency for a given mass) in a Gaussian beam, and can come with the enhanced scattering dispersion needed for torques and damping forces.

Restoring forces alone under continuous excitation by perturbations lead to oscillations with growing amplitude, with the sail eventually leaving the beam and shooting off course. To keep these in check, damping forces and torques are required, which oppose velocities away from the beam axis and oppose destabilising angular velocities. Damping in the vacuum of space is tricky. One way to achieve it is by altering the magnitude of restoring forces and torques over time through parametric or adiabatic damping. This can be done through active feedback by periodically switching the laser off, or more naturally, through the sail's dispersive scattering response and slow change of wavelength (Doppler shift) over the course of acceleration. More promising suggestions involve explicitly velocity-dependent forces, such as adding an internal damped degree of freedom into the sail (like earthquake dampeners in skyscrapers) or using relativistic optical effects (e.g. the relativistic Doppler effect, used in fields of study like cavity optomechanics). For instance, damping the rotational motion of a lightsail is possible using the Doppler redshift and blueshift of light on the portions of the sail rotating away from and towards the laser, respectively. The advantage of photonic structures like gratings is apparent for these methods, as they can dramatically enhance any change in scattering due to minute changes in wavelength – but taking advantage of this dispersion over the full Doppler shifted band is challenging.

The best way to stabilize sails is still an active topic of theoretical investigation, and we don't yet have the technology to make finely structured thin membranes on the scales required for interstellar missions. However, increasingly large, high-quality membrane photonic crystals have been fabricated in the lab (Figure 1c, d). Researchers have measured non-specular scattering from fabricated gratings and found consistency with the requirements of self-stabilizing lightsail motion. Moreover, direct radiation pressure measurements of restoring forces using a torsional pendulum apparatus or tethered membranes have been successful.

CONCLUSION

Lightsails are the most promising spacecrafts for reaching near-relativistic speeds, opening highways into new star systems, and providing answers to the fundamental question of our place in the universe. While not entirely realistic with today's technology, based on current pace of progress in laser and fabrication technology, many researchers believe an interstellar mission could be launched within a few decades.

Many challenges, such as large-scale lasers and nanofabrication, will find progress driven by other industries and scientific endeavours including telecoms, semiconductor manufacturing, defence, and fusion research. We expect that once these technologies mature enough for the price tag of the required lasers to be within grasp of large-scale science projects such as LIGO or the LHC, the prospect of an interstellar mission will encourage more targeted research into practical implementations of lightsail missions, which in turn will spur technological advances across scientific fields. The comparison with LIGO is one that often appears among lightsail researchers. To us, lightsails are where LIGO was fifty years ago, when the detection of gravitational waves, requiring the resolution of shifts less than the width of a nucleus over 4 km interferometric arms, seemed to be farfetched science fiction. Many technical challenges were posed without obvious solutions. But with the resolve of visionary scientists, gravitational wave astronomy is now a reality, and perhaps in another fifty years, incentivised by progress in photonic technologies, interstellar probes will be too.

ACKNOWLEDGEMENTS

This research was supported by an Australian Government Research Training Program (RTP) scholarship.

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