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Interstellar lightsails: enhancing asymptotic stability through optimised metasurface design

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Lightsails are an enticing proposal for spacecraft that can travel to nearby star systems such as Alpha Centauri. Their advantage is their ability to reach speeds up to $0.2c$ when accelerated by high-power lasers. One significant obstacle to lightsail missions is that the sail experiences perturbations (e.g. from laser-beam noise or atmospheric effects) that act to eject the sail from the beam. The sail has a tight mass budget, therefore, any transverse motion must be passively corrected using restoring mechanisms and damping mechanisms. Previous studies only determined how to trap the sail within the beam using carefully designed metamaterial membranes to scatter light momentum in appropriate directions. However, the restoring mechanism produces oscillations that may be exacerbated by perturbations, destabilising the sail. Hence, a damping mechanism to reduce the velocity of perturbations is also required. However, damping does not occur naturally in the vacuum of space. One novel solution utilises the Poynting-Robertson drag, which weakly damps mirror-based sails, but which can be enhanced by orders of magnitude for optimised metasurfaces. Recently, the Poynting-Robertson model was extended to completely account for restoring and damping dynamics for a sail propelled by a Gaussian laser beam. The derived relativistic equations of motion highlight that translational and rotational damping can be greatly enhanced by engineering the sail's optical-scattering angular and frequency dispersion, but no such optimisations were performed. Here, we employ linear stability analysis to guide the optimisation of metasurfaces to achieve asymptotically stable sails. We find 3–4 times enhancement in damping coefficients compared to mirror-based sails over the $0.2c$ -acceleration bandwidth, and 10000 times enhancement in the rotational degree of freedom over narrow ranges. Then, we showcase the significant damping in nonlinear dynamical simulations.

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