Poynting-Robertson stabilization of relativistic lightsails

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Light sails are a promising technology intended for the next generation of space travel, using the transfer of momentum from photons to propel the spacecraft to relativistic speeds. During acceleration, the light sail must remain within the photon beam. Recent papers have shown mirror and metasurface configurations [1, 2] that can introduce restoring forces towards the centre of a finite beam. However, in the absence of damping, the restoring force leads to transverse oscillations. When the accelerating beam is turned off, any residual oscillations will lead to the craft going off-course.

There is thus a need to introduce a damping force to the system – that is, a velocity dependent, non-conservative force ($F = -\alpha v$). Coupling motion to damped internal degrees of freedom could be used to this end [2], but implementation is difficult in a low mass-budget sail. Instead, light itself may be able to dampen the oscillation, as observed in the Poynting Robertson (PR) effect in which the motion of dust particles orbiting stars is damped by perpendicularly incident light, through the Doppler effect and relativistic aberration. When analysing dust particles, PR literature averages out the angular distribution effectively assuming all light interactions to be isotropic [3]. Considering an angular distribution of scattered intensity $F(\theta)$ based on a 2D light sail geometry, we express the damping forces acting on the light sail in the direction of the incident light (x) and perpendicular to it (y) in the form:

$$F_x = A \int_0^{2\pi} F(\theta) \cos\theta d\theta \quad (1) \qquad\qquad F_y = A \int_0^{2\pi} F(\theta) \sin\theta d\theta \quad (2)$$

Simulating these forces for simple V-shaped light sail systems shows the dependence of transverse force on transverse velocity, which is linear for small transverse velocities (the likely regime of the sail). Additionally, these forces are of the approximate order of magnitude to effectively dampen the oscillations anticipated for the sail. The generalisation of the PR effect thus provides a promising avenue for stabilisation of the sails, although torque and angular stability will also need to be considered.

[1] O. Illic and H. Atwater. "Self-stabilizing photonic levitation and propulsion of nanostructured macroscopic objects". In: *Nature Photonics* 13 (2019), pp. 289–295

[2] M. Z. Rafat *et al.* "Self-Stabilization of Light Sails by Damped Internal Degrees of Freedom". In *Physical Review Applied* 17 (2022) 024016

[3] J. Klacka et al. "The Poynting Robertson Effect: a critical perspective". In: *Icarus* 232 (2012), pp. 249–262