

IAC–20–D4,4,5,x58922

Mitigation of Interplanetary Media Impacts for Laser-Driven Interstellar Travel

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The interaction of the main laser of a laser-driven lightsail with dust grains of the interplanetary media is considered. During the acceleration phase of the lightsail, the impact of dust grains on the lightsail is of particular concern due to the impact event compromising the low laser absorptivity of the sail. This could cause significant deposition of laser energy into the sail, resulting in its total destruction. Thus, the potential use of the drive laser to significantly deplete the number of dust grains in the volume to be swept by the passage of the sail would be highly advantageous. In this paper, the laser beam is modeled as a standard Gaussian intensity distribution. This profile is incorporated into the considered ablation model, which evaluates vaporization conditions for graphite, alumina, and iron grains travelling at 0.2c. A sail diffraction analysis determines the most beneficial sail geometry for the ablation model. Finally, the use of crystal channeling is studied to assess potential applications for dust grain mitigation during the cruise phase of the lightsail.
Keywords: Interstellar Flight, Directed-energy, Interplanetary Dust, Diffraction, Ablation,

1. Introduction

Currently, the farthest spacecraft, Voyager 1, is the first spacecraft to pass the heliopause with a velocity of 17 km/s. With a flight duration of 42 years, the total distance covered by Voyager 1 only accounts for 0.05% of the distance needed to reach α-Centauri. In order to achieve the accelerations needed to complete missions farther into interstellar space, there needs to be a drastic shift from conventional propulsion technology. Directed energy propulsion is generally considered to be one of the most promising techniques in order to achieve interstellar travel within a reasonable timescale. The use of collimated photons from Earth-based lasers that would propel a highly reflective metallic sail was first proposed by Forward in 1962 and further elaborated by Marx in 1966 [1], [2]. However, constraints associated with the material properties of metallic sails limits the total laser flux that could be used to accelerate the sail to reach the desired velocity needed for interstellar flight. Recent advancements in photonics have allowed the development of a modular and scalable phased array of lasers capable of reaching the high fluxes needed for interstellar flight. As presented by Lubin, the earth-based laser array system is a modular system with a power density of 1 kW/m^2. This system would have the capability of producing a power output of 100 GW with a 10-km-sized array (the flux needed to achieve a significant fraction of light speed). This laser system will be focused onto a 1-m-diameter lightsail until the desired velocity of 0.2c is reached before exceeding the focal length of the 10-km laser array (approximately occurs at 0.1 AU) [3]. With the high flux delivered to the sail during its acceleration phase, the sail must have very low absorptivity (in the order of 10^{-6}) to prevent it from being melted or vaporized by the laser flux. Thus, the necessity that the lightsail has low absorptivity makes dielectrics a promising candidate material.

A significant concern that will need to be addressed is the possibility of impacts of the interplanetary media, particularly dust grains, during the acceleration phase of the lightsail. Since the acceleration phase occurs near Earth, the spatial concentration of interplanetary dust particles (IDPs) is approximately two orders of magnitude greater than the spatial density in the interstellar media [4]. Thus, assuming a spatial density of 10^{-20} kg/m^3 of a 1-µm-sized dust grain, the sail may be exposed to approximately 14 impacts cm^{-2} over the total 0.1 AU acceleration run [5]. These dust grain impacts may compromise the low absorptivity of the lightsail, causing a significant amount of the laser flux to be absorbed. The absorption of even a minor amount of laser flux could lead to a catastrophic loss of the entire lightsail. The damage propagation associated with the absorbance of high laser irradiance in a dielectric material is analogous to *fiber fuse*, a widely studied phenomenon occurring in fiber optics. At low flux, local absorption-induced damage can propagate across the sail at speeds on the order of 1 m/s. For high flux scenarios, damage propagation could emulate a laser-supported detonation (LSD) wave propagating at speeds on the order of km/s [6]. Dust grain impacts during the interstellar cruise are also a concern, however, there has been some research done on the interaction of relativistic spacecraft with the interstellar medium.In particular, Hoang et al. identify damage mechanisms associated with the interaction of a relativistic spacecraft with gas atoms and dust grains in the interstellar medium and present several ways to protect the spacecraft throughout the journey to α-Centauri [7].

In this paper, we will demonstrate the plausibility of utilizing the irradiance of the drive laser to potentially mitigate the risks associated with the interplanetary media during the acceleration phase. Other techniques to shield against the interstellar media (ionized gas and dust) during the cruise phase will also be investigated.

2. Order of Magnitude Analysis

As presented by Landis, dielectric materials have the ability to reach up to 99.9995% reflectance by increasing the number of alternating layers of high and low refractive indices [8]. However, by increasing the number of bilayers, the total mass of the sail would increase, resulting in negatively affecting the acceleration of the lightsail. These considerations suggest that the optimal lightsail may be a single layer transparent dielectric where the reflectivity is maximum when the thickness of the sail is one quarter the wavelength of the light measured inside the film. As presented by Parkin, if we optimize for the sail's acceleration, the optimal sail thickness, in terms of the figure of merit for sail acceleration per unit beam power, would occur at a sail thickness of $\frac{\lambda}{7}$. In particular, Parkin identified that a lightsail that is 1000 nm thick with 99.9% reflectance would accelerate 2.5 times slower than the 100-nm-thick sail with 25% reflectance, thus suggesting a primarily transparent sail design should be used [9]. The balance of the laser flux passing through the sail can be used to potentially ablate the dust grains prior to impacting the sail. Thus, an order of magnitude analysis is used to estimate the total time needed to vaporize the grain. The total time to vaporize the grain is estimated by an energy balance approach:

$$m\left[c\,\Delta T_{\mathrm{sp}} + \Delta h_{\mathrm{f_{vap}}}\right] = \alpha\, I_0\, A\, \Delta t \qquad [1]$$

Assuming spherical dust grain of diameter d and density ρ, the total time of vaporization can be solved:

$$\Delta t = \frac{2\,\rho\, d\left[c\,\Delta T_{\mathrm{sp}} + \Delta h_{\mathrm{f_{vap}}}\right]}{3\,\alpha\, I_0} \qquad [2]$$

Due to the nature of the IDP complex morphology, for the idealized ablation scenario, the absorptivity coefficient may approach unity ($\alpha \approx 1$). To highlight the "worst-case scenario", we will assume a grain of carbon (graphite) to be the material of choice given its high vaporization temperature (T_{vap} = 3400K) and large enthalpy of vaporization ($\Delta h_{\mathrm{vap}} = 3.6 \times 10^7$ J/kg). For a laser flux of $I_0 = 100$ GW/m^2, Eq. 2 gives a total time of vaporization of ≈ 0.5 µs. This ideal solution is supported by the Holman laser ablation model, where an equation for the velocity of the ablation front is developed [10]. By using the same parameters, the velocity of the ablation front is determined to be 1300 m/s, which yields a 10^{-10} s total vaporization time for a 1 µm grain. The results of these simple calculations appear quite promising, allowing a more realistic model to be implemented. A concern that must be addressed is the interaction between the driver laser and dust grains which are less than the wavelength of the driver laser. Such smaller grains could significantly decrease the relative amount of flux the dust grain is able to absorb during the ablation process. Particles in this size range are characterised as being within the Rayleigh regime, where the absorption coefficient could be as low as 10^{-6}. However, the scaling of the absorptivity for dielectric materials with grain size d is represented as

$$\alpha \sim \frac{d}{\lambda} \qquad [3]$$

Substituting this relation in Eq. 2 demonstrates that the dependence on the size of the grain (d) is independent of the total vaporization time thus suggesting that smaller grains could potentially be vaporized as well.

3. Beam Profile

In order to conduct the dust grain ablation analysis, the drive laser was modeled as a focused Gaussian beam. Based on the Gaussian beam approximation, laser irradiance could be determined. The analysis conducted involves representing the phased array of lasers as a collimated Gaussian beam. Thin lens approximation equations will be used in order to approximate the transient focused spot size of the Gaussian beam as it is phased locked onto the sail.

Gaussian Beam Equations

Assumptions made:

i. The focal length of the array is equal to the distance from the array to the lightsail. This assumption is valid using thin lens approximation to focus a collimated Gaussian beam [11].

ii. The Gaussian beam will propagate symmetrically on both sides of the lightsail.

iii. The focused beam waist becomes the new beam waist of the Gaussian beam.

Focused beam waist [11]:

$$\omega_{\mathrm{f}} = \frac{4\,\lambda\, f}{\pi\,\omega_o} \quad [4]$$

Divergence angle:

$$\theta = \frac{4\,\lambda}{\pi\,\omega_o} \quad [5]$$

Rayleigh range:

$$Z_{\mathrm{Rayleigh}} = \frac{\pi\,\omega_{\mathrm{f}}^2}{\lambda} \quad [6]$$

Beam Waist:

$$\omega(z) = \omega_{\mathrm{f}} \left[1 + \left(\frac{z}{z_{\mathrm{R}}} \right)^2 \right]^{\frac{1}{2}} \quad [7]$$

Intensity distribution:

$$I(r,z) = I_0 \left(\frac{\omega_{\mathrm{f}}}{\omega(z)} \right)^2 \mathrm{e}^{\left(-\frac{2r^2}{\omega(z)^2} \right)} \quad [8]$$

4. Laser Interaction

The laser ablation model utilized for this analysis consisted of evaluating a system representing the phase change process for a perfect spherical dust grain from solid to vapor. The spherical dust grain is treated as a radiating blackbody with increasing laser irradiance as the dust grain approaches the lightsail. Equation 9 determines the time needed to reach the vaporization temperature of the dust grain whereas Eq. 10 determines the time needed to complete an isothermal phase change process. The absorption coefficient parameter α was implemented to analyze the effects on laser flux absorptivity with total ablation time. For the purpose of this analysis, the vaporization front of the dust grain during the ablation period will not be model due to the negligible time associated with the mass removal rate at the vaporization point.

By solving the ODEs:

$$m\,c\,\frac{\mathrm{d}T}{\mathrm{d}t} = \alpha\, I(t)\, \left(\frac{\pi}{4}\right)\, d^2 - \sigma\, 4\, \pi \left(\frac{d}{2}\right)^2 T^4 \quad [9]$$

Solving change in energy using:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \alpha\, I(t)\, \left(\frac{\pi}{4}\right)\, d^2 - \sigma\, 4\, \pi \left(\frac{d}{2}\right)^2 T^4 \quad [10]$$

By numerical solving these equations, an approximate solution for the vaporization point relative to the sail is determined.

Results and Discussion

As shown in Fig.1, the ablation analysis consisted of numerically solving the transient heating of a 1 μm graphite dust grain as it approaches the focused Gaussian beam profile emanating from a relatively fixed lightsail positioned at 0.1 AU from the laser. Based on the position of the lightsail, the dust grains will be approaching at a velocity of 0.2c (as viewed from the reference frame of the sail). The results of these more detailed calculations demonstrate the relative position where the dust grain will be vaporized ahead of the sail. As demonstrated in Eq. 2, the results of this ablation analysis also applied to nano-scale grains that are in the Rayleigh regime. The following graphs present the numerical results for the vaporization of dust grains travelling at 0.2c towards a lightsail positioned at 0.1 AU for a) graphite grain b) alumina grain c) iron grain:

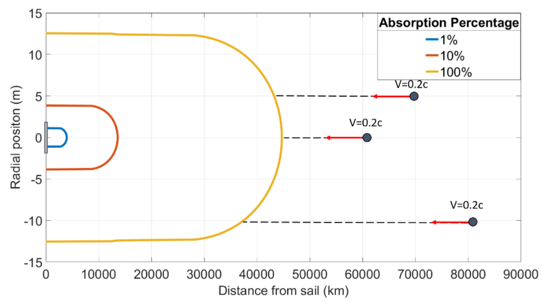

Fig. 1: a) Graphite Grain

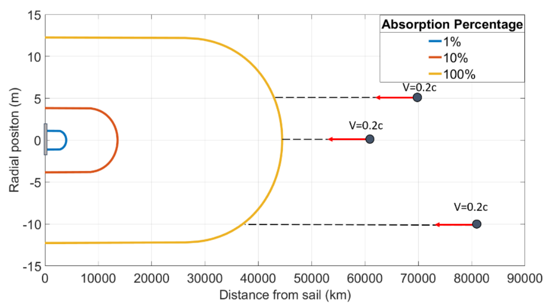

Fig. 2: b) Alumina Grain

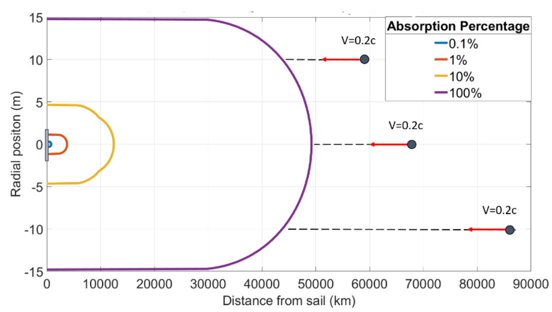

Fig. 3: c) Iron Grain

Based on the results achieved, the driver laser may have the ability to ablate the dust grains prior to impacting the sail. This study also concerned other grain materials (alumina, iron, etc.) likely to be present in dust grains in the solar system [12]. Although the results seen promising, a more realistic ablation model will be implemented in future work.

5. Diffraction

So far, we have been considering the laser-matter interaction to see if the power of the laser could ablate the kinds of dust grains the sail will encounter in the interplanetary media. Now, for a more complete treatment of the problem, we would need to incorporate the sail into the analysis. More specifically, we are interested in investigating the possibility of using the sail to further collimate the beam. There are two main ways of going about this, which depend on whether we choose the sail to be a refractive or diffractive optic. Today, the cheapest and simplest way of collimating a beam is through the use of a compound lens system. This technique relies on the index of refraction of the chosen lenses. Implementing this technique in the case of the light-sail would restrict our choice of materials. Considering the fact that the sail would likely incorporate embedded nanotechnology and would need to be made of meta-materials, this scenario is less than ideal.

In 1984, Forward suggested the use of moon-sized Fresnel Zone Plates to focus light of a laser beam onto a laser-driven light-sail for better acceleration [13]. In our case, we study implementing these Fresnel Zone Plates into the design of the lightsail in order to assess the possibility of ablating incoming dust grains. The use of Fresnel Zone Plates is in fact another common way beams are collimated. This technique relies on diffraction, which corresponds to the spilling of light around an object's edges. It depends on the geometry of the sail, which imposes less material restrictions than refractive optics. A Fresnel Zone Plate (FZP) is a circular diffraction grating, made of concentric zones, that acts as a thin lens. FZPs can either be Soret FZPs, which are a succession of alternating opaque and transparent zones, or Rayleigh-Wood FZPs, which switch out the opaque zones for phase-reversal zones [14]. The latter is typically made of meta-materials. Soret FZPs have a zero-order efficiency *of 10.1%, while Rayleigh-Wood FZPs have an efficiency of 40.5% [14]. For the purpose of this study, we will be considering the more efficient of the two, Rayleigh-Wood FZPs.

In theory, collimating a beam would mean that the optic the beam is going through has a focal length f approaching infinity. In practice, the goal is to obtain the longest focal length possible. FZPs can have multiple focal points where different relative intensities are observed. However, FZPs have one focal point with a maximum relative intensity of unity. We are interested in evaluating the distance of this focal point. From our ablation model, this

*The diffraction efficiency η corresponds to the power of the diffraction peak of an order of interest over the power of the incident beam. Here, the zeroth order corresponds to the diffraction peak of maximum intensity [15].

distance would need to be on the order of 10^8 m, to such an extent that an incoming dust grain has enough time to be ablated. The focal distance of this point is given by the relation:

$$f = \frac{r^2}{n\,\lambda} \qquad [11]$$

where f is the focal point of maximum intensity, r is the outer radius, n is the number of zone plates and λ is the wavelength of the beam. For a 1-m outer radius and 100 zone plates (a common number for FZPs), the obtained focal distance is 10^4 m. Even if the number of zone plates were to be reduced to 10, the focal distance would still be three orders of magnitude less than the distance required by the ablation model. Beyond the focal point of maximum intensity, the beam diverges, further reducing the flux intensity. It is well known that the diffraction profile of a circular stop presents a Poisson-Arago spot, where the axial relative intensity is found to be unity. Typically this spot is extremely small. However, from our simulated diffraction model, the spot size is found to be as large as the sail at distances relevant to the ablation model. Comparing the FZP results to the diffraction profile of a simple circular stop, there appears to be no obvious benefit to the use of FZPs over simply having a circular lightsail.

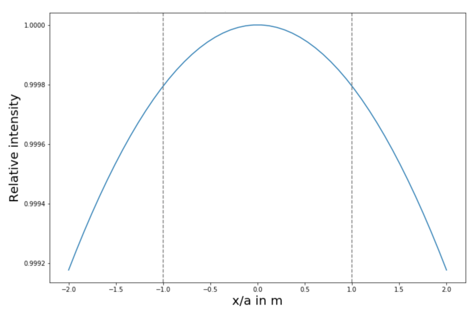

Fig. 4: Diffraction profile of a circular stop for incident Gaussian beam: $\lambda = 10^{-6}$, $\omega_{\mathrm{f}} = 0.5$ m, aperture $a = 0.5$ m, distance $z = 10^8$ m

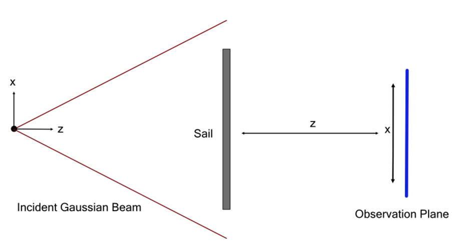

Fig. 5: Defining the observation plane with respect to the lightsail

6. Dust Grain Mitigation during Cruise Phase

Although the dust mitigation during the acceleration phase is the primary concern, the concepts proposed for the mitigation of the interstellar media during the cruise phase will now be considered. During the cruise phase, the drive laser will be off, which significantly decreases the potential damage a single dust grain impact may pose, since the laser flux can not longer be absorbed by the sail. However, due to the longevity of the interstellar cruise, the interaction of the relativistic spacecraft with gas atoms and dust grains presented in the interstellar medium throughout the cruise phase may pose a significant issue. In particular, Hoang et al. suggest that gas bombardment could potentially erode the spacecraft a total depth of 0.1 mm, whereas dust bombardment could erode a total of 0.5 mm of the lightsail thickness throughout the interstellar cruise towards α-Centauri. A further complication is that dust grain impacts at these speeds cannot be experimentally simulated in the laboratory due to the inability to accelerate the grains to the required energy [5]. Therefore, a proposed strategy to decrease the total erosion of the sail would be to fly the lightsail edge-on, greatly minimizing the total cross-sectional area it presents to the interstellar medium. The edge-on oriented lightsail will still be exposed to a flux of the ions travelling at 0.2c, which have an energy of about 19 MeV per nucleon. The use of a magnetic field to deflect the incoming particles has been well established in the conventional astronautics literature and could potentially be used to protect the lightsail. The radius of curvature of a charged particle in a static magnetic field is given by the gyroradius:

$$r_{\mathrm{c}} = \frac{m\,V}{Q\,B} \qquad [12]$$

By using Eq. 12, assuming a particle travelling at 0.2c towards the edge-on oriented lightsail exposed to a 1 T field, the length of the magnetic field needed to deflect the particle away from the lightsail is defined as:

$$L_{\mathrm{m}} = \sqrt{\frac{v\,t}{\mathrm{B}\,(\frac{Q}{m})}} \qquad [13]$$

The total deflection angle is then calculated by using:

$$\theta = \sqrt{\frac{t}{r_{\mathrm{c}}}} \qquad [14]$$

where t represents the minimum thickness the particle need to deflect by. The total length of the 1 T magnetic field needed to deflect the particles by 0.02 mrad is 10^{-3} m. Although magnetic field deflection could deflect the incoming particles, producing a 1 T magnetic field around the lightsail poses a significant engineering challenge.

6.1 *Crystal Channeling*

A promising alternative to magnetic field deflection is using a phenomenon known as crystal channeling. Crystal channeling uses a series of curved bilayers of crystals (e.g., silicon) to deflect the incoming flux of high energy nuclei. The silicon crystals act as a mean to steer the ions by oscillating them between a series of crystallographic planes as shown in Fig. 6.

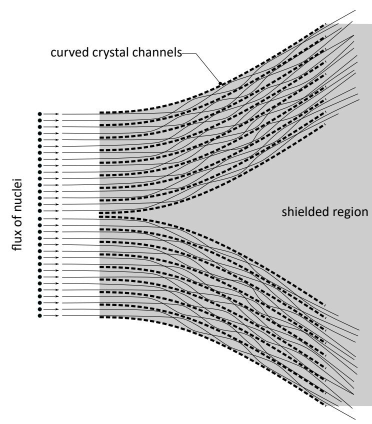

Fig. 6: Deflection of high energy ion using a series of bent silicon crystals

This technique has been previously used in high energy particle accelerators as a means to collimate beams of charged particles with energy levels varying from MeV up to TeV. The critical radius of curvature for this technique is given by:

$$r_c = \frac{m\,V^2}{Q\,E_c} \qquad [15]$$

where E_c is the average interatomic electrical field intensity; for a silicon crystal, $E_c \approx 0.5 \times 10^{12}$ V/m [16]. A limiting condition for the deflection efficiency of the crystal channeling technique is that the incoming flux of particles must be highly collimated. The critical angle (θ_c) needed for crystal channeling varies between the different selection of crystals. However, silicon crystals have shown to deflect ions with energy levels of 19 MeV per nucleon through a critical angle of 1.22 mrad [17]. For particles entering the channels at an angle of incidence greater than the critical angle, a technique known as multi-volume reflection (MVR) can be used in order to increase the critical acceptance angle of the crystals. Multi-volume reflection involves geometrically stacking several curved layers together providing highly efficient deflection over a wide range of entrance angles at high energy levels. In particular, Breese et al. [18] demonstrate that the bending efficiency using MVR significantly outperforms the capabilities of individual channeling crystals. The acceptance angle of the MVR structure could also be $\sim$ 20 times greater than the acceptance angle of bent crystal channeling [18]. Thus, high energy protons which exhibit large incident angles could potentially be diverted away from the sail using a MVR technique.

6.2 *Dust Shield*

The crystal channeling technique could be incorporated into a means for protecting against the impact of interstellar dust grains during the cruise phase.

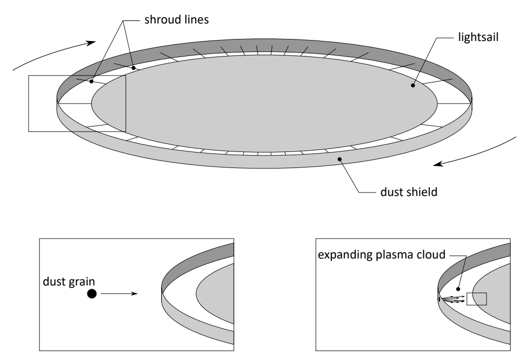

Fig. 7: Edge-on sail orientation with dust shield

As shown in Fig.7, a ring of thin material (similar to the lightsail itself) would surround the edge of the sail and act as a dust shield. From the mechanism outlined by London and Early [19], the impact between the dust shield and the dust grain would convert the dust grain into an expanding plasma. This high energy plasma would then be incident upon the leading edge of the sail. Due to the interaction between the dust grain and dust shield, the gain in the grain electron energy would be approximately 0.3 keV [19]. Assuming the "worst-case scenario" that the grain protons gain an equivalent amount of energy, the most probable thermal velocity of the ion is 2.4×10^5 m/s. Thus, the maximum deflection angle could potentially be gained by the ions is 4 mrad. The use of bent crystal channels attached to the edge of the lightsail will then be used to deflect the upcoming charged ions.

7. Conclusion

The current ablation model shows the plausibility of vaporizing a dust grain up to 50 000 km ahead of the sail. We can take advantage of the circular geometry of the sail to retrieve the original intensity of the laser beam. With the provided preliminary analysis, there appears to be no benefit to a seemingly more sophisticated system of Fresnel Zone Plates over a simple circular sail geometry. Crystal channeling coupled with a dust shield appears to be a promising technique that can potentially protect the sail during its cruise phase. Multi-volume reflection could also be potentially used to increase the critical acceptance angle of the silicon crystal channels.

Future work

The next step of the research is to add additional complexity to the current ablation model. The more realistic model will incorporate the intensity distribution of a transient beam profile coupled with the diffraction of the drive laser around the lightsail.

Acknowledgements

The authors would like to thank Emmanuel Duplay for his contributions in creating the figures. The authors also thank Philip Lubin, David Cooke, and Lilian Childress for stimulating discussions. This work was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant.

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