Acta Astronautica 114 (2015) 1–5

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Safety criteria for flying E-sail through solar eclipse

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ARTICLE INFO

Article history:
Received 16 February 2015
Received in revised form
10 April 2015
Accepted 12 April 2015
Available online 20 April 2015

Keywords:
Electric sail
Mission design
Eclipse

ABSTRACT

The electric solar wind sail (E-sail) propellantless propulsion device uses long, charged metallic tethers to tap momentum from the solar wind to produce spacecraft propulsion. If flying through planetary or moon eclipse, the long E-sail tethers can undergo significant thermal contraction and expansion. Rapid shortening of the tether increases its tension due to inertia of the tether and a Remote Unit that is located on the tether tip (a Remote Unit is part of typical E-sail designs). We analyse by numerical simulation the conditions under which eclipse induced stresses are safe for E-sail tethers. We calculate the closest safe approach distances for Earth, Moon, Venus, Mars, Jupiter, Ceres and an exemplary 300 km main belt asteroid Interamnia for circular, parabolic and hyperbolic orbits. We find that any kind of eclipsing is safe beyond approximately 2.5 au distance, but for terrestrial planets safety depends on the parameters of the orbit. For example, for Mars the safe distance with 20 km E-sail tether lies between Phobos and Deimos orbits.

1. Introduction

The solar wind electric sail (E-sail) is a newly discovered way of propelling an interplanetary spacecraft by employing the thrust produced by the natural solar wind plasma stream [1,2]. The solar wind dynamic pressure is tapped by long, thin, centrifugally stretched and positively charged tethers (Fig. 1). According to numerical estimations, the E-sail could produce ~500 nN/m thrust per unit length [3]. Thus an E-sail with 2000 km total tether length (for example with 80 tethers 25 km long each) would produce ~1 N of thrust at 1 au [4]. The thrust scales as $1/r$, where r is the solar distance [3]. The predicted thrust versus propulsion system mass ratio (1 N thrust at 1 au and 100–200 kg mass) is high enough that it would enable a large class of previously unattainable missions in the solar system such as sending a ~200 kg probe at more than 50 km/s speed out of the solar system to make in situ measurements of interstellar space beyond the heliopause [5].

The metallic tethers of the E-sail (Fig. 2, [7,8]) can be up to 20 km long. In theory and depending on the design, they might be even longer. If the E-sail spacecraft enters into planetary eclipse, the tethers (mass per unit length of the four-wire aluminium tether is 11 g/km) cool down relatively rapidly because they are thin and thus have low heat capacity. Cooling causes the tethers to contract. Because the tethers are long, contraction corresponds to significant movement of the tether tip. Typically the tether tip contains a Remote Unit (~0.5 kg mass) to which non-conducting auxiliary tethers are connected [4]. The contracting tether has to pull the masses residing at the tether tip inward, which requires certain force. This force causes first an increase of the tether tension and together with the centrifugal force afterwards also some oscillations. If the tension gets too high, the tether might break mechanically.

Throughout the paper we assume 20 km tethers and use the value 1 cN as the maximum allowed extra tension due to thermal contraction, which is 20% of the baseline overall tether tension of 5 cN at 20 km tether length. If shorter tethers are used, risks due to thermal contraction are smaller.

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http://dx.doi.org/10.1016/j.actaastro.2015.04.006
0094-5765/

Nomenclature

A	Cross-sectional area of tether base wire, $1.96 \times 10^{-9}\ \mathrm{m}^2$
au	Astronomical unit, 149 597 871 km
c_p	Heat capacity of tether material (aluminium), $910\ \mathrm{J\,kg^{-1}\,K^{-1}}$
E	Young elastic modulus of tether material, 73 GPa
f	Uneclipsed fraction of the solar limb
F	Tether tension
I	Solar radiative flux at spacecraft location (power per area)
k	Spring constant of tether
L	Tether length
L_0	Rest length of tether at temperature T_0
ΔL	Length change (elongation) of tether due to tension
m	Tether end mass, 1 kg
r	Solar distance of eclipsing body
R_B	Radius of eclipsing body
R_E	Radius of Earth
r_w	Radius of base wire of E-sail tether, 25 μm
t	Time
T	Tether temperature
T_0	Tether initial temperature before eclipse
v_∞	Speed at infinity for hyperbolic orbit
α	Optical absorptance of tether surface, 0.1
α_L	Coefficient of linear thermal expansion of base wire, $2.31 \cdot 10^{-5}\ \mathrm{K^{-1}}$
ϵ	Thermal infrared emissivity of tether surface, 0.04
ρ_w	Mass density of tether material (aluminium), $2700\ \mathrm{kg\,m^{-3}}$
σ	Stefan–Boltzmann constant, $5.67 \cdot 10^{-8}\ \mathrm{Wm^{-2}\,K^{-4}}$

The purpose of this paper is (1) to predict the eclipse induced extra tether tension for different solar system bodies and types of trajectories and (2) to map the boundary between safe and unsafe parameter space valid for the baseline E-sail tether design. This information is needed when designing E-sail missions.

2. Numerical model of tether eclipsing

Consider a single E-sail tether which we assume to be a 4-wire Heytether [7] made of $r_w = 25$ μm[1] radius aluminium base wire and three 25 μm diameter loop wires. The load-bearing member is the base wire except at rare positions where micrometeoroids have broken the base wire. Hence we can ignore the elasticity of the loop wires in analysing eclipsing induced tensile stresses. We assume that there is an end mass m at the tip of the tether which includes the mass of the Remote Unit and its share of the auxiliary tethers. Typically, $m = 1$ kg is clearly larger than the mass of the tether (~0.2 kg at 20 km length), and we neglect the mass of the tether when solving the equation of motion of the tether. In thermal calculations the mass of the tether is essential and is included.

We denote the tether's rest length at its initial temperature T_0 by L_0. We assume a coefficient of linear thermal expansion $\alpha_L = 2.31 \cdot 10^{-5}\ \mathrm{K^{-1}}$ so that the tether's rest length at temperature T is

$$L = [1 + \alpha_L (T - T_0)] L_0. \tag{1}$$

The tether aluminium base wire has Young elastic modulus $E = 73$ GPa, cross-sectional area $A = \pi r_w^2$ and spring constant

$$k = \frac{EA}{L_0}. \tag{2}$$

When put under tension F, the tether lengthens an amount ΔL such that Hooke's law holds:

$$F = \begin{cases} k\Delta L, & \Delta L > 0, \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

The tether base wire is heated by solar radiation whereas it is cooled by infrared emission. If the tether is perpendicular to sun direction, its thermal evolution is described by

$$c_p \rho_w \pi r_w^2 \frac{dT}{dt} = f \alpha 2 r_w I - 2\pi r_w \epsilon \sigma T^4 \tag{4}$$

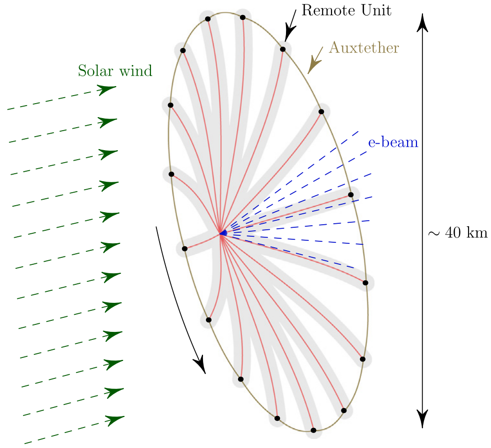

Fig. 1. Spinning E-sail in the solar wind. The solar wind force bends the charged main tethers. The tethers are surrounded by the electron sheaths which are shown schematically by shading.

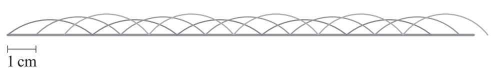

Fig. 2. Micrometeoroid resistant four-wire E-sail Heytether.

[1] See Nomenclature.