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Drag force on solar sails due to absorption of solar radiation

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Abstract

We consider a special relativistic effect, known as the Poynting–Robertson effect, on various types of trajectories of solar sails. Since this effect occurs at order v^ϕ/c, where v^ϕ is the transversal speed relative to the sun, it can dominate over other special relativistic effects, which occur at order v^2/c^2. While solar radiation can be used to propel the solar sail, the absorbed portion of it also gives rise to a drag force in the transversal direction. For escape trajectories, this diminishes the cruising velocity, which can have a cumulative effect on the heliocentric distance. For a solar sail directly facing the sun in a bound orbit, the Poynting–Robertson effect decreases its orbital speed, thereby causing it to slowly spiral towards the sun. We also consider this effect for non-Keplerian orbits in which the solar sail is tilted in the azimuthal direction. While in principle the drag force could be counter-balanced by an extremely small tilt of the solar sail in the polar direction, periodic adjustments are more feasible.

Keywords: Solar sails; Poynting–Robertson effect

1. Introduction

Solar electromagnetic radiation can be transmitted, reflected, absorbed and emitted by a solar sail. It is well known that the reflected, absorbed and emitted portions of the radiation can be used to propel the solar sail, due to the force of the electromagnetic pressure. What is less known is that the absorbed portion of the radiation induces a drag force on the solar sail, thereby diminishing its transversal speed relative to the sun. While this force is relatively small, it can have a long-term cumulative effect on the trajectories of solar sails. In particular, the effect of this drag force can be rather dramatic on the heliocentric distance of solar sails in long-range escape trajectories, while solar sails in bound orbits will spiral inwards to the sun.

The aforementioned drag force on solar sails is associated with the Poynting–Robertson effect, which was first investigated for small spherical particles by Poynting (1904). Although it is now realized that this is a special relativistic effect associated with the finite speed of light, Poynting's paper was actually published a year before Einstein's paper on special relativity. This effect was reconsidered in 1937 by Robertson as a manifestly special relativistic effect (Robertson, 1937). Then starting from a paper by Whipple and Wyatt (1950), the Poynting–Robertson effect was used for modeling the orbital evolution of dust particles orbiting the sun and, in particular, accounted for the drag force which causes dust particles to slowly spiral inward towards the sun. Various refinements of the original analysis have been made, such as including the leading-order effect of curved spacetime around the sun for particles of various shapes, (see Kocifaj and Klacka, 2008; Bini et al., 2009 and references therein for details).

While there has been much research devoted to the influence of the Poynting–Robertson effect on the motion of dust grains, the Poynting–Robertson effect was only recently considered for solar sails in bound orbits (Kezerashvili and

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Vázquez-Poritz, 2010). In this paper, we consider the Poynting–Robertson effect for solar sails in escape trajectories and further elaborate on the cases of bound heliocentric and non-Keplerian orbits. From the rest frame of the solar sail, this effect is associated with the nonradial component of the absorbed solar radiation, due to the relative motion between the sun and the solar sail. From the rest frame of the sun, this results from the solar sail that absorbs solar radiation and then emits it in the forward direction relative to its motion.

Note that this paper is not about trajectory design and their limitations due to the temperature of solar sail. The closest approach to the sun is clearly restricted by the temperature limitations of the solar sail. Since this is an open issue, we present our results for a fairly broad range of heliocentric distances. We have placed special emphasis on the physical aspects of the matter. Furthermore, we use an idealized model in which the sun is a point-like emitter and variations in solar luminosity are not considered. We are making the working assumption that we can use time-averaged quantities, and that such fluctuations will not change our results regarding the long-term cumulative role played by the Poynting–Robertson effect. For simplicity, we are making the assumption that both sides of the solar sail have equal emissivity.

This paper is organized as follows. In Section 2, we present the orbital equations for a solar sail orbiting in the plane of the sun, which takes into account the drag from the Poynting–Robertson effect. In Section 3, we investigate the diminished heliocentric distance which results from this drag effect on solar sails in escape trajectories. Next, we consider how the Poynting–Robertson effect causes an initially circular orbit to slowly spiral in towards the sun. In Section 4, we consider bound orbits whose plane passes through the center of mass of the sun. In Section 5, we consider "non-Keplerian orbits" for which the orbital plane does not pass through the center of mass of the sun. Conclusions follow in Section 6.

2. Orbital equations

The total force exerted on the solar sail due to solar radiation is the result of reflection, absorption and emission by the solar sail of a portion of the absorbed radiation. When the solar electromagnetic radiation interacts with the solar sail material, it undergoes diffuse as well as specular reflection. The acceleration due to the diffuse reflection is directed along the normal to the antisun surface area, while the acceleration due to the specular reflection is directed opposite to the reflected radiation. In addition, the acceleration produced by the absorption of the solar radiation is directed along the incident radiation. Moreover, a portion of the absorbed radiation will be re-radiated from the front and back sides of the solar sail, which leads to an acceleration normal to whichever surface has the smaller emissivity. We will bring into consideration an additional force due to absorption which has not been taken into account.

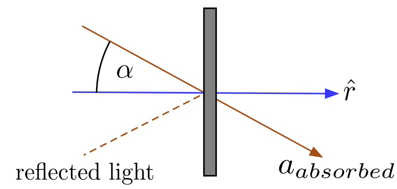

Fig. 1. Reflected light yields an acceleration in the radial direction, whereas absorbed light leads to an acceleration at an angle α with respect to the radial direction, due to the Poynting–Robertson effect.

In the Newtonian framework, the solar radiation is purely radial. Thus, for the case in which the surface of the solar sail is directly facing the sun, the force due to the solar radiation pressure (SRP) is directed radially outwards. However, as a special relativistic effect, the solar radiation has a nonzero transversal component in the frame of reference of the solar sail. This is due to the relative transversal speed $v^\phi = r\dot{\phi}$ between the solar sail and the sun, where r is the heliocentric distance and ϕ is the angular coordinate. In particular, in the rest frame of the solar sail, the solar radiation propagates at an angle $\alpha = \sin^{-1}(v^\phi/c)$ with respect to the radial direction. Therefore, the absorbed portion of this radiation leads to a force with a component opposite the direction of motion. This drag effect is generally known as the Poynting–Robertson effect, which occurs at order v^ϕ/c, and dominates over other special relativistic effects which are at order v^2/c^2. Note that we are neglecting the redshift in wavelength of the solar radiation due to the radial velocity of the solar sail, which is a higher-order effect.

We will first consider a solar sail whose surface is directly facing the sun and whose motion is restricted to lie within the heliocentric plane. The portion of light absorbed leads to an acceleration directed at an angle α with respect to the radial direction denoted by the unit vector $\hat{r}$, as depicted in Fig. 1.

We will be using the efficiency parameter $0.5 \leqslant \eta \leqslant 1$ where $\eta = 0.5$ (1) corresponds to the total absorption (total reflection) of solar radiation by the surface of the solar sail. The fraction of light reflected is $2\eta - 1$ and the fraction of light absorbed is $2(1-\eta)$. According to McInnes (1999), a conservative value for the efficiency parameter is $\eta = 0.85$. Throughout this paper, we will present results for $\eta = 0.75$. However, we have performed calculations for both values of η and have confirmed that, while our results depend on η, they are not too sensitive to its precise value. The acceleration due to the portion of light that is reflected by the solar sail is directed in the radial direction and has a magnitude of

$$a_{reflected} = \frac{(2\eta - 1)\kappa}{r^2}\cos^2\alpha, \quad \kappa \equiv \frac{L_s}{2\pi c\sigma}, \tag{1}$$

where σ is the mass per surface area of the solar sail and $L_S = 3.842 \times 10^{26}$ W is the solar luminosity.

We are not considering fluctuations in the solar radiation and are taking a time-averaged luminosity. In Eq.