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Dynamics, geometry and solar sails☆

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Abstract

This note focuses on some dynamical aspects of a solar sail. The first part of the paper is a survey of the use of dynamical systems tools to control a solar sail near an unstable equilibrium point of the Earth–Sun system. The second part focuses on new results on the dynamics near an equilibrium point of a sail near an asteroid. The main tool is a reduction to the centre manifold to focus on the bounded motions. In both cases, the role of the geometrical structures of the phase space is highlighted.

Keywords: Periodic orbits; Centre manifolds; Halo orbits

1. Introduction

Dynamical systems have proven to be a useful tool for the design of space missions. For instance, the use of invariant manifolds is now common to derive control and transfer strategies. In this note we focus on a specific kind of low thrust propulsion, known as solar sailing. Solar sailing is based on the use of large membrane mirrors to take advantage of the solar radiation pressure to propel the spacecraft. Although the acceleration produced is smaller than the one achieved by a traditional chemical thruster, solar radiation pressure acts continuously and it is unlimited in time. This makes some long term missions more accessible, and opens a wide new range of possible applications that cannot be achieved by a traditional spacecraft.

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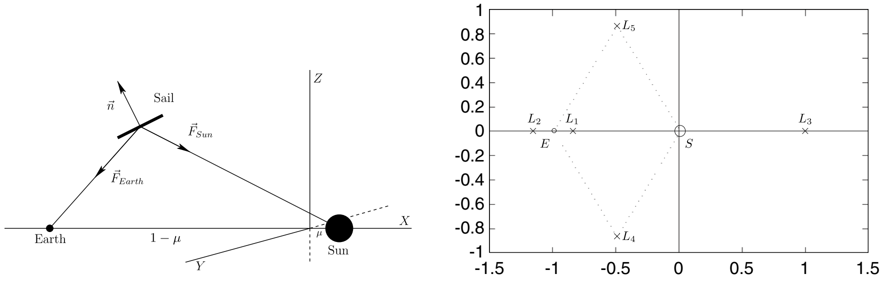

Fig. 1. Left: Scheme of the forces acting on the sail. Right: The five equilibrium points of the Restricted Three-Body Problem.

Up to now, three solar sails have been successfully deployed in space: IKAROS, NanoSail-D2 and LightSail-A. IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) is a Japan Aerospace Exploration Agency experimental spacecraft with a 14×14 m^2 sail. The spacecraft was launched on May 21st 2010, together with Akatsuki (Venus Climate Orbiter). On December 8th 2010, IKAROS passed by Venus at about 80.800 km. NanoSail-D2 is a small solar sail (10 m^2, 4 kg) deployed by NASA on January 2011 in a low Earth orbit, that reentered the atmosphere on September 17th 2011. LightSail-A is a small test spacecraft (32 m^2) of the Planetary Society, that was launched on May 20th 2015 and deployed its solar sail on June 7th 2015. It reentered the atmosphere on June 14th 2015.

In this paper we will focus on the dynamics of a solar sail in a couple of situations. We will introduce this problem focusing on a solar sail in the Earth–Sun system. In this case, the model used will be the Restricted Three Body Problem (RTBP for short) plus solar radiation pressure (see Fig. 1, left). The effect of the solar radiation pressure on the RTBP produces a 2D family of "artificial" equilibria, coming from the well known equilibria of the RTBP (see Fig. 1, right or [25] for more details). This new equilibria can be parametrised by the orientation of the sail. We will describe the dynamics around some of these "artificial" equilibrium points. We note that, due to the solar radiation pressure, the system is Hamiltonian only for two cases: when the sail is perpendicular to the Sun—sail line; and when the sail is aligned with the Sun—sail line (i.e., no sail effect). The main tool used to understand the dynamics is the computation of centre manifolds, for both the Hamiltonian and non-Hamiltonian cases.

The second example is the dynamics of a solar sail close to an asteroid. Note that, in this case, the effect of the sail becomes very relevant due to the low mass of the asteroid. We will use, as a model, a modified Hill problem that includes the effect of the solar radiation pressure, to describe some aspects of the natural dynamics of the sail.

The paper is organised as follows. Section 2 is a short introduction to the dynamics of a solar sail and its applications. Section 3 is a summary of some previous work of the authors on the use of the geometry of the phase space to control a sail. Section 4 introduces a modification of the classical Hill problem to model a solar sail close to an asteroid. Section 5 explains the so-called reduction to the centre manifold for the previous model, and finally Section 6 uses the centre manifold to describe the phase space.

2. Solar sail models

Here, a solar sail is modelled as a flat surface that reflects a large portion of the sunlight, while a small portion is absorbed. The reflected photons produce an impulse in the normal direction of

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