

**Fundamental Physics in Space
at
Faculdade de Ciências, Universidade do Porto**

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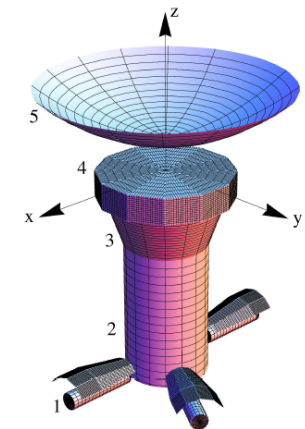
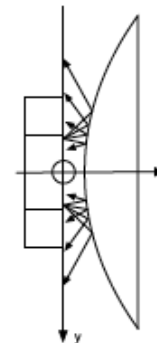
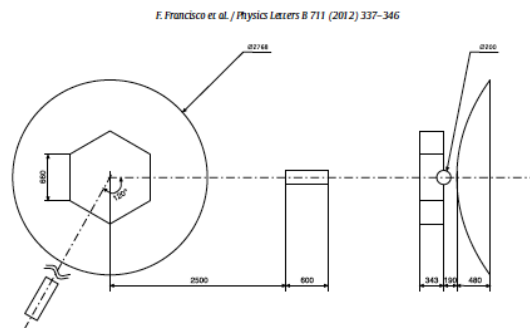
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Thermal analysis of spacecraft

- Modelling and computation of small accelerations due to thermal effects (Solution for the Pioneer and Cassini anomalies)



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- Co-author of Portugal's National Strategy for Space (O.B. 2004)
- Member of the Galileo Science Advisory Committee of ESA (OB, 2008-2013)

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Gravity Control and Possible Influence on Space Propulsion: A Scientific Study



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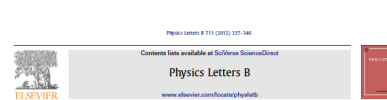
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Modeling the reflectance thermal contribution to the acceleration of the Pioneer spacecraft

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ABSTRACT

We present an improved method to compute the radiative acceleration transfer in the Pioneer 10 and 11 spacecraft that takes into account both diffuse and specular reflection. The method allows for more reliable results regarding the thermal contribution of the large area plates, reflecting previous findings. One of these experiments was carried out from June 6 to July 7, 2002, while the probe was in a solar conjunction. The results from the data harvested during this one-month period allowed for constraining the γ parameter of the PPN formalism, which quantifies the amount of curvature generated per unit mass to within $(2.1 \pm 2.3) \times 10^{-5}$ of unity, the most accurate bound obtained so far [1].

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1. Introduction

1.1. General background

For over a decade the Pioneer anomaly has stood out as an open question in physics. The existence of this apparently constant non-gravitational acceleration in the Pioneer 10 and 11 spacecraft was first raised in 1986 by a team of scientists at the Jet Propulsion Laboratory (JPL) [1]. In the subsequent years, the anomalous acceleration was studied in detail, with the latest results pointing towards a constant value of $(8.74 \pm 1.23) \times 10^{-10} \text{ m/s}^2$ [2].

The existence of this effect has been independently confirmed through alternative data analyses [3–5]. At least two of these analyses do also allow for a non-constant anomalous acceleration [3, 5].

Throughout the last decade, numerous attempts have been made to explain the Pioneer anomaly. These can be mainly divided into two categories: conventional [6,7] and non-conventional explanations [8–11]. It has also been shown that the Kuiper Belt is not the cause of the anomalous acceleration, considering several models for its mass distribution [12].

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1.2. Thermal effects

The initial assessment of systematic effects made in Ref. [2] assumed that any acceleration arising from thermal dissipation would be too small to account for the Pioneer anomaly. However, early in this discussion, some argued that thermal effects could provide a viable explanation for the detected anomaly. Indeed, two works argued, albeit on a qualitative basis, that there was sufficient on-board thermal energy to account for the anomalous acceleration [13,14].

Some time later, the effort to obtain a quantitative description of the effect of the thermal emissions of the spacecraft gained momentum, with three independent studies underway for the last few years. The first results were published by our team in 2008 [15,16]. The estimates we performed using a method based on a distribution of point-like Landoltian-like thermal radiation sources, which at first glance seemed not to be the most realistic, the method can effectively model the main contributions at work, while keeping the inherent simplicity, computational flexibility and speed [13,16].

It is also noted that between 10% and 60% of the observed acceleration can be explained by the thermal emissions of the spacecraft itself [13,16]. This was confirmed by early figures produced by the team at JPLM [15]. It has also been reported that an analysis is underway by the JPL based team [16].

This letter builds on the previous work and presents a comprehensive analysis based on a direct modelling of reflection, in opposition to estimates based on surface reflectivity, as obtained in Ref. [15]. In addition, a parametric analysis is carried out in

PHYSICAL REVIEW D 86, 042004 (2012) Modeling the nongravitational acceleration during Cassini's gravitation experiments

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In this paper we present a computation of the thermally generated acceleration of the Cassini probe during its solar conjunction experiment, obtained from a model of the spacecraft. We build a thermal model of the vehicle and perform a Monte Carlo simulation to find a thermal acceleration with a main component of $(3.01 \pm 0.31) \times 10^{-7} \text{ m/s}^2$. This result is in close agreement with the estimates of this effect performed through Doppler data analysis.

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1. INTRODUCTION

The Cassini mission was launched on October 15, 1997. Its goal was to reach Saturn and also included a set of planned experiments designed to test general relativity. One of these experiments was carried out from June 6 to July 7, 2002, while the probe was in a solar conjunction. The results from the data harvested during this one-month period allowed for constraining the γ parameter of the PPN formalism, which quantifies the amount of curvature generated per unit mass to within $(2.1 \pm 2.3) \times 10^{-5}$ of unity, the most accurate bound obtained so far [1]. During the solar conjunction experiment, the nongravitational acceleration had to be filtered out as well as possible and, in particular, the significant contributions from solar radiation pressure and from anisotropic thermal emission of the probe itself. Due to the unavailability of any straight forward procedure to obtain the valid thermal emissions from a model of the spacecraft, data from Doppler measurements were used to estimate the component of the acceleration that is constant relative to the spacecraft orientation. The obtained values for the thermally generated acceleration reveal that the largest component is aligned with the Earth-spacecraft axis and amounts to $3 \times 10^{-7} \text{ m/s}^2$ towards the Earth. The other two components are smaller and measured orthogonally to the orbital plane and on the orbital plane, and are found to be about $4 \times 10^{-8} \text{ m/s}^2$ and $1 \times 10^{-7} \text{ m/s}^2$, respectively. These components, however, have large error estimates associated with their determination [1].

The aim of this paper is to consider the problem of obtaining the value of the thermally generated accelerations and directly respond to the stated difficulty in extracting them from a model of the spacecraft itself. It is shown that reliable results can be obtained by using the physical and computational framework previously developed to study the acceleration generated by thermal emissions in the Pioneer 10 and 11 spacecraft, in the context of the problem that became known as "the Pioneer anomaly" [2–4].

II. POINTLIKE SOURCE METHOD

A. Motivation

The pointlike source method is an approach that maintains a high computational speed and a broad degree of flexibility, allowing for an easy analysis of different contributions and scenarios. The method was designed to keep all the physical features of the problem at glance and all steps easy to scrutinize. Although it can be argued that this simplicity and transparency was achieved at the expense of accuracy, a history of test cases can be performed to test the robustness of the results [2,3]. These test cases validate the approach, as they show that, for reasonable assumptions, the possible lack of accuracy caused by our modeling approach is much smaller than the accuracy in the characterization of the acceleration itself.

This method was also designed to consider parameters involving a large degree of uncertainty: this is related to the geometrical and material properties of the various spacecraft elements, which in most cases do not have well-known baseline (before launch) values, and have extended extended periods of degradation in space. By assigning a statistical distribution to each parameter, based on the available information, and generating a large number of

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GRAVITY CONTROL PROPULSION:
TOWARDS A GENERAL RELATIVISTIC APPROACH

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Evaluation of gravity control concepts should be examined with respect to currently known physical theories. In this work we study the hypothetical conversion of gravitational potential energy into kinetic energy using the formalism of general relativity. We show that the energy involved in the process greatly exceeds the Newtonian estimate, given the nature of general relativity. We conclude that the impact of any gravity manipulation for propulsion greatly depends fundamentally on its exact definition.

Keywords: Gravity control, general relativity, energy-momentum pseudo-tensor

1. INTRODUCTION

Access to space using currently available propulsion systems is extremely limited both in distance and in time. In recent years the interest in unconventional propulsion proposals has grown in the hope that new forms of propulsion, that increase the range of spacecraft while reducing the trip time, are discovered.

Several conceptual mechanisms have been proposed to radically improve the performance of propulsion systems, such as warp-drives [1,2], transient mass fluctuations [3], anti-gravity [4] or gravitational shielding effects [5]. While some of these proposals are only conceptual, others such as the gravitational shielding have been tested and proved unfruitful [6]. Many of these systems are based on the effect of the manipulation of mass and gravity in a rocket's motion. The study of the impact on propulsion systems' performance of such manipulations has been previously considered and demonstrated that even if gravity could be controlled or modified it would not lead to any breakthrough in propulsion systems [7].

Other conceptual devices (e.g. the space drive) go even further, idealizing a form of propulsion without any reaction mass that would somehow manipulate space-time and matter to create propulsive forces. One of the possible energy sources for such a device, as suggested in Ref. [8], is gravitational potential energy. For concreteness we shall argue along the energy considerations as suggested in that reference. In there, it has been proposed that these systems could not be analyzed using rocketry metrics and that their full potential could only be understood in terms of the energetic considerations [8]. We understand that this energy based study should be undertaken, nonetheless it should be regarded with caution, especially when trying to estimate the potential benefits of converting gravitational potential energy into kinetic energy. Furthermore, we believe that the results of any approach in the context of the Newtonian framework should be considered with great care.

In the current work we approach this space drive problem from the general relativity point of view. For this purpose we

Nomenclature	
c	speed of light = $3 \times 10^8 \text{ m.s}^{-1}$
δ	inertial mass modification factor
ϵ	gravitational mass modification factor
ϵ'	gravitational field modification factor
G	gravitational constant = $6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
I_{sp}	specific impulse
v_p	propellant velocity
$G_{\mu\nu}$	Einstein tensor
$T_{\mu\nu}$	energy-momentum tensor
$t_{\mu\nu}$	energy-momentum pseudo-tensor of gravitational field
$g_{\mu\nu}$	metric tensor
g	metric determinant
$\Gamma_{\mu\nu}^\alpha$	metric connection
$\delta^3(\vec{r} - \vec{r}_0)$	Dirac delta function

consider the energy-momentum pseudo-tensor in order to estimate the energy in a given of space-time volume. As expected, we find that the resultant energy is considerably larger than the Newtonian estimate based on the difference in the gravitational potential between two distinct points.

Before we present our computation and discuss its implications, we review some of the results presented in Ref. [7] concerning gravity manipulation based on rocketry metrics.

2. ROCKETRY METRICS

Classical propulsion systems rely on Newton's mechanics. The

TESTING THE FLYBY ANOMALY
WITH THE GNSS CONSTELLATION

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We propose the concept of a space mission to probe the so called *flyby anomaly*, an unexpected velocity change experienced by some deep-space probes using earth gravity assists. The key feature of this proposal is the use of GNSS systems to obtain an increased accuracy in the tracking of the approaching spacecraft, mainly near the perigee. Two

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Comparison of Space Propulsion Methods for a
Manned Mission to Mars

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We assess the possibility of reducing the travel time of a manned mission to Mars using different propulsion methods and keeping the mass at departure within bounds. For the sake of comparison we used representative systems of different state of the art or proposed technologies, from the chemical engine to the "Pure Electro-Magnetic Thrust" (PEMT) concept, using a nuclear engine proposed by Rubbia. A mission architecture based on existing proposals is suggested in order to estimate the mass budget that influences the performance of the propulsion system. Pareto curves of the duration of the mission and time of flight versus mass of mission are drawn. We conclude that the ion engine technology, combined with the classical chemical engine, is the one which yields the shortest mission times with the lowest mass, and that chemical propulsion alone is the best to minimise travel time. The results obtained using the PEMT suggest that it is a more suitable solution for farther destinations than Mars.

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