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Transport of Nanoparticles in the Interplanetary Medium

M. de Juan Ovelar, J. M. Llorens, C. H. Yam, and D. Izzo

Advanced Concepts Team, ESTEC

European Space Agency, Noordwijk, The Netherlands

ABSTRACT

The dynamic behaviour of nanoparticles in the interplanetary medium is subject to forces of a different nature often negligible for larger objects like satellites. Many theoretical models have been developed to explain the dynamics and transport mechanisms of cosmic dust. Building on this knowledge, we study the solar radiation pressure on artificial nanospheres, as a first step to assess the possibility of establishing artificial material fluxes in the interplanetary medium.

1. Introduction

Dynamics in the interplanetary medium constitutes the backbone of the development in space technology. Based on this knowledge, it is possible to design a large variety of missions as to achieve several scientific objectives. It is only possible to achieve control on the dynamics of an object by knowing the environment characteristics and designing the object accordingly.

The main issue this work explores is the possibility of performing a similar design process over extremely small particles which could be particularly useful in new applications like: gravitational fields analysis around natural objects in space, NEO tracing techniques, calibration of onboard instruments in satellites, control of solar radiation over objects, etc…

In order to answer this question we have analysed the behaviour of natural cosmic dust looking for the particle key properties (e.g. coating material and thickness) we should engineer to control its dynamic behaviour.

Due to their small size, particles naturally present in the interplanetary medium are subjected to different forces, which are usually negligible for larger objects like satellites. We have first analysed the main forces acting on small natural particles in the solar system finding that the pressure exerted by the solar radiation on a particle is of the same order as the gravitational attraction for particle sizes at the nanoscale and acts in the opposite direction.

Neglecting any other forces acting on the particle, it is possible to control its final dynamical response by controlling the ratio between the radiation and the gravitational force, i.e. the β parameter, as it is known in the literature [2].

We propose in this paper to design an artificial nanoparticle in such a way that we can tailor its radiation pressure response and hence control its dynamics. We consider here as an artificial nanoparticle, a spherical core covered with a coating. The thickness and material properties of the coating are then the key parameters which will allow us to tailor the final optical response of the nanoparticle.

In Section 2, we describe the theoretical framework in which the study has been developed and establish the validity range of the approximations made. Section 3 contains the results on the analysis of the dependence of β with respect to the coating properties and a discussion on the engineering possibilities of out approach on β. Once the relation between the coating properties and β has been studied we show the results of a dynamical problem in Section 4.

We should note that along the paper we have considered the idealised case of a nanoparticle subject only to the radiation force and solar gravity. As we will show in the next section, the contribution of the Lorentz force is also of relevance for determining realistic orbits. However its implementation requires of an accurate modelling of the space environment (plasma parameters) and solar magnetic field [3]. For the sake of simplicity, we decided to constraint ourselves to the dynamical problem defined only by the two forces mentioned above. We study a modified Lambert problem to find the optimal coating that allows, in a given time frame, to reach selected targets starting from an Earth trailing orbit (the case of Mars is shown).

In this simple framework, the nanoparticle can be considered as moving in Keplerian orbits subjected to a decreased gravity regime and the particle coating can thus be conveniently considered as a control parameter on the solar mass. This creates an interesting and new trajectory design problem that we solve here for the first time showing the possibility to reach the selected target with no required initial Δv.

2. Radiation–particle interaction: Key properties

The interaction between forces present in the solar system and small particles determines their dynamic response, this is, the spatial and temporal evolution of the orbit. To explore these interactions and decide which ones are determinant in our case of study, one should be first referred to the vast bibliography related to cosmic dust in the Solar System [2] [6].

The main forces acting over a small particle of diameter smaller than 1 μm in the solar system can be reduced to the gravitational force (F_G), the radiation pressure force (F_R), the Lorentz force (F_L), the Poynting-Robertson drag force (F_{PR}) and the solar wind forces (F_{SW}) [6]. At his range of sizes, the Poynting-Robertson drag force and the solar wind force become negligible compared to the gravitational, radiation and Lorentz forces. Thus, we can reduce our problem considering the study of an artificial particle subjected only to these forces.

An accurate description of the Lorentz force implies some difficulties due to its nature. This force comes from the interaction between particle charge and the planetary and solar magnetic fields. It is well established that a neutral particle orbiting around the Sun, gets a positive charge due to various effects like photoemission of electrons, sticking and penetration of plasma particles, and secondary electron emission due to bombardment of energetic plasma [3] and therefore it gets affected by the presence of magnetic fields. Furthermore, the solar magnetic field introduces two major difficulties. At distances ~ 1 AU, i.e. in the region of interest for the missions we are interested in, the field is described by equally important radial and azimuthal components [4]. This implies that in principle, the Lorentz force will present radial, azimuthal and vertical components, which will complicate enormously the system dynamics. In addition, the solar magnetic field changes its orientation every ~ 11 years and exhibits quite frequent fluctuations linked to its activity. The mathematical model should incorporate these effects, since their time scale are of the same order of magnitude than the mission time of flight.

In summary, the actual calculation of the resultant Loretz force on the particle requires a complete model of the solar magnetic field and plasma environment in the solar system. Therefore, as a first approach to the problem, we consider only in this study the gravitational force (F_G) and the radiation pressure force (F_R), acting in the same line but opposite direction.

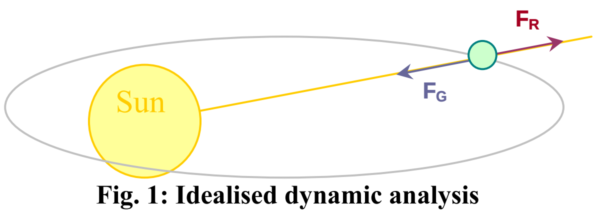


Fig. 1: Idealised dynamic analysis

The equation defining the gravitational force is well known from Newtonian mechanics:

$$\vec{F}_{\mathrm{G}} = -G\cdot\frac{M_* m_{\mathrm{Pa}}}{r^3}\cdot\mathbf{r}, \qquad (1)$$

where G is the gravitational constant, M_* is the central body mass, m_{Pa} is the particle mass and $\mathbf{r}$ is the particle's position vector. This equation gives us the acceleration of the particle and therefore defines its trajectory if no other force is present.

Radiation Pressure force, can be classically explained as the net effect of the transfer of momentum taking part between molecules constituting matter and an incoming electromagnetic field. Photons, coming from an electromagnetic wave, carry energy and momentum, and thus when they meet a particle, part of their energy and momentum is transferred. The effectiveness of this process can be described by the absorption and scattering cross sections, both represented in the so called *efficiency for radiation pressure factor* (Q_{pr}), and both depending on the particle optical properties (complex dielectric function $\varepsilon=\varepsilon_1+j\varepsilon_2$, and complex refractive index, $N=n+jk$). The resultant force is expressed as follows:

$$\vec{F}_{\mathrm{R}} = \frac{L_* A_{\mathrm{Pa}} Q_{\mathrm{pr}}}{4\pi c r^3}\cdot\mathbf{r}, \qquad (2)$$

where L_* is the stellar luminosity, A_{Pa} is the particle cross section, c is the speed of light in vacuum and $\mathbf{r}$ is again the particle's position vector.

Taking into account these two forces, we can express the resulting net force as:

$$\vec{F}_{\mathrm{Tot}} = (F_{\mathrm{R}} - F_{\mathrm{G}})\cdot\frac{\mathbf{r}}{r}. \qquad (3)$$

It is useful then to define a parameter, usually called $\boldsymbol{\beta}$ in the cosmic dust bibliography, evaluating the ratio between them as follows:

$$\beta = \frac{\left|\vec{F}_{\mathrm{R}}\right|}{\left|\vec{F}_{\mathrm{G}}\right|} = \frac{1}{4\pi c}\cdot\frac{A_{\mathrm{Pa}} Q_{\mathrm{pr}}}{m_{\mathrm{Pa}}}\cdot\frac{L_*}{GM_*}. \qquad (4)$$

This parameter depends on both stellar and particle characteristics. If we define the Sun as our central body, the first and second factors in equation (4) remain constant and therefore it is derived that β depends only on particle properties as mass, size and the efficiency for radiation pressure factor determined by the material composition.

It is interesting to remark that β is independence of the particle position, i.e. once the particle and the central body are defined β remains constant along the particle's trajectory.

The net force can be then expressed in terms of this parameter as

$$\vec{F}_{\mathrm{Tot}} = (1-\beta)F_{\mathrm{G}} \cdot \left(-\frac{\mathbf{r}}{r}\right), \qquad (5)$$

from what we can derive that the resultant effect of the radiation pressure acting over the particle is to counteract gravity and therefore, the final trajectory for the particle will be determined by its motion in a modified central gravity field, depending on the β parameter.

For values of β between 0 and 1, the solution for the particle's trajectory could be a parabolic, elliptic or hyperbolic orbit with the sun as focus. For β=1, the radiation pressure counteracts completely the gravitational force and therefore the particle follows a linear trajectory unless other forces come into action. For values larger than 1, the only possible solution is a hyperbolic trajectory with the sun in the outer focus, meaning that the particle is rejected out of the system by radiation in which is usually called an escape orbit.

In order to detect the basic properties of the particle that affect this parameter we now describe the particle dependent factor in equation (4) in terms of basic properties obtaining the following:

$$\begin{aligned} A_{\mathrm{Pa}} &= \pi R_{\mathrm{Pa}}^2 \\ m_{\mathrm{Pa}} &= \frac{4}{3}\pi R_{\mathrm{Pa}}^3 \rho_{\mathrm{Pa}} \end{aligned} \quad \Rightarrow \quad \boxed{\beta = B \cdot \frac{Q_{\mathrm{pr}}}{\rho_{\mathrm{Pa}} R_{\mathrm{Pa}}}} \qquad (6)$$

where B is a constant value including the Sun characteristics dependent factor, ρ_{Pa} is the particle density and R_{Pa} is the particle radius.

Looking at this expression we can finally infer that the dynamic response of the particle in this idealised case is completely governed by the particle density, radius and optical properties (permittivity or refractive index).

3. Engineering β

Our proposal to engineer the β value of an artificial nanoparticle consists of designing a coating for a spherical particle so that we are modifying its optical response at will.

In order to evaluate the β value of a nanoparticle, we have calculated the absorption and scattering cross sections, and therefore the radiation pressure acting over the particle by means of the Multiple Elastic Scattering of the Multipole Expansions (MESME) [5]. This formalism is general enough to cope not only with single particle, but also with particle clusters in different arrangement.

We show in Fig. 2 a plot illustrating typical values of β and its dependence with the particle radius (R_{Pa}), for spherical particles made of uniform materials. In all cases we have considered real values of the material dielectric function. The black curve corresponds to the ideal case of constant efficiency factor for the radiation pressure Q_{pr}=1, approximation known as geometrical optics. It serves for the purpose of establishing when wave optics needs to be applied. As it is shown in the Figure, for sizes larger than ~ 1 μm it is a good approximation to assume a constant $Q_{pr.}$

Such an approximation is commonly used for extended bodies (such as solar sails or satellite) but fails to describe the interaction between nanoparticles and the solar electromagnetic radiation.

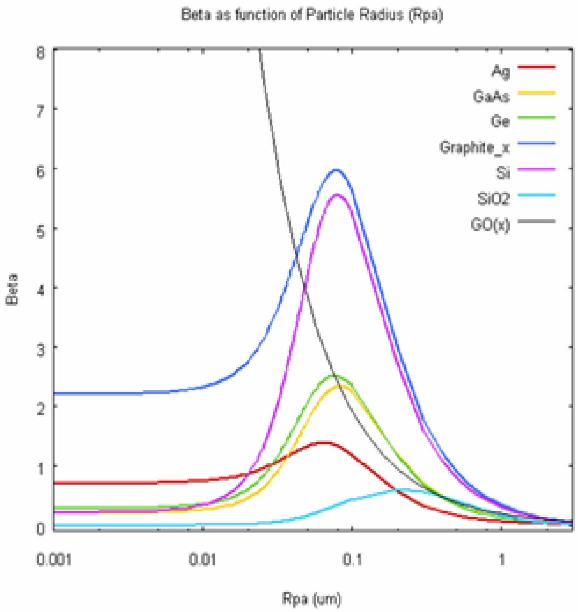


Fig. 2: β dependence on particle size for different materials

For almost all materials, there is a β maximum at ~ 0.1 μm. These are expected results, given that the interaction between particles and electromagnetic radiation reaches its maximum value for particle sizes of the order of $\lambda/2\pi$, which for the Sun (the maximum intensity of the sun spectrum is at ~ 0.6 μm.), corresponds to ~ 0.1 μm [2].

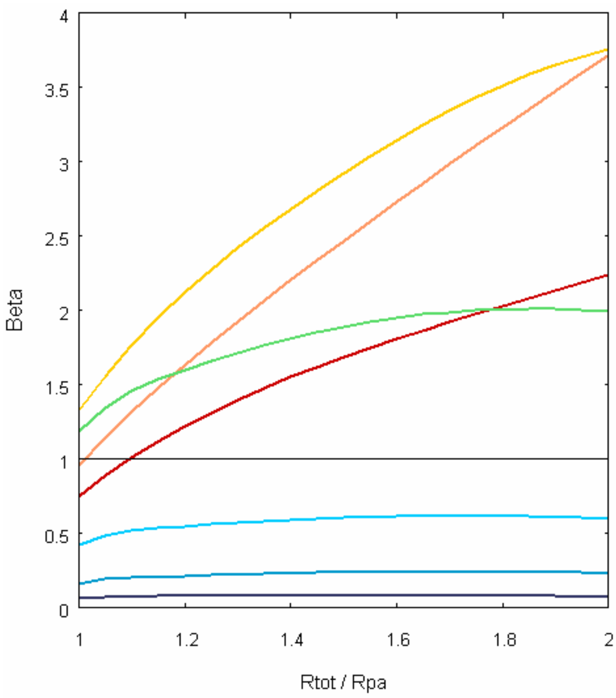
The particular features of the real and imaginary parts of the material dielectric function determine the optical response of the particle. For materials as graphite, of densities ~ 2.00 g/cm^3 and high values of the imaginary part of the refractive index (k, which is tightly related to the absorption), we find that radiation pressure can overcome gravitational force by a factor of 6 for certain particle sizes (0.1 μm). On the other hand, materials like silver, exhibiting also high values of k, are mostly governed by the gravitational effect due to its much larger density (10,41 g/cm^3).

During the study we have analysed many combinations of materials. The system consisting of an Ag core and a graphite coating is a representative one. In this system the core material exhibits low values of β, while the coating material presents much higher values.

In Fig. 3, we present the variation of β with respect to the coating thickness for different particle sizes. The coating thickness (d) is expressed through the ratio R_{Tot}/R_{Pa}, meaning that for a ratio equal to one there is no coating (d=0) and for a ratio equal to two the coating is as thick as the core (d=R_{Pa}). The table on right hand side of Fig. 3 presents the β values for these two limiting cases.

From these results, it is possible to infer that the coating introduces a big change in β for small particle sizes (R_{Pa} < 50 nm). For larger sizes, the gravitational interaction becomes dominant and the coating slightly affects the value of the bare particle. In other systems, as Si/graphite, there is a change in the sign of the slope of the curves for sizes larger than ~ 0.1 μm (results not shown).

This results shows that our approach introduces a change in β, which allows us to tailor the dynamical response of the nanoparticle. However, the dependence of β on the coating thickness depends to a great extent on the material system. Therefore, our approach lacks of transferability from one system to another and each case needs to be analyse in particular.



R_{pa} (μm)	β_1	β_2
0.01	0.75	2.23
0.025	0.96	3.71
0.05	1.33	3.75
0.1	1.18	1.98
0.25	0.42	0.60
0.5	0.16	0.23
1.0	0.06	0.073

Fig. 3: Values of β as a function of R_{Tot} for different core radius. The line colour in the plot is linked to the cell colour in the right table pointing to the corresponding R_{pa}. The core material is Ag and the coating material is graphite.

4. Nanoparticle transfer orbits

To illustrate the benefits of our approach in engineering β, we solve a practical case. We aim at minimizing the velocity increment a spherical nanoparticle needs in order to reach a given target from a starting point in the solar system by applying a coating to it.

Considering a nanoparticle in an Earth trailing orbit, which means the particle has escaped Earth's gravity but it is still under the influence of the Sun, we want to answer the following question: for a given launch date, what β parameter gives the smallest maneuver cost (Δv) to reach a given target body?

For this first simulation we plan to transfer a nanoparticle to Mars.

We consider a range of launch dates and time of flight and solve the two-point boundary value problem (known as the Lambert problem) in the "weakened" gravitational field of the Sun (see Eq. (5)). The manoeuvre cost is computed as the difference Δv between the required departure velocity and the initial orbital velocity of the nanoparticle (in this case, the same as the Earth).

The optimization process is carried out minimizing the Δv including β as a parameter by means of the gravitational parameter known as $\boldsymbol{\mu} = \boldsymbol{GM_*}$, which using the relation shown in Eq. (5) can be redefined as a variable depending on β as follows

$$\mu'(\beta) = \mu \cdot (1-\beta). \tag{7}$$

In Figure 3, we present the Δv cost for a various launch dates (Date Of Launch, on the abscissa axis) and times of flight (TOF, on the ordinate axis) for different β values: 0, 0.4, 0.6, 0.8. The value β=0 represents no effect of the radiation pressure acting over the particle (F_R=0).

These contour plots are commonly known as "pork-chop" plots and are characterised by periodic areas of minimum values of Δv (shown in blue) which here vary in position and shape depending on β, illustrating the potential applications of this concept.

It is important to note that the current algorithm we are using to calculate this plots does not admit values of β larger than 1, i.e. negative values of μ which will imply a negative value for the Sun's mass. In a further work, this problem will be solved adapting the algorithm to include such cases.

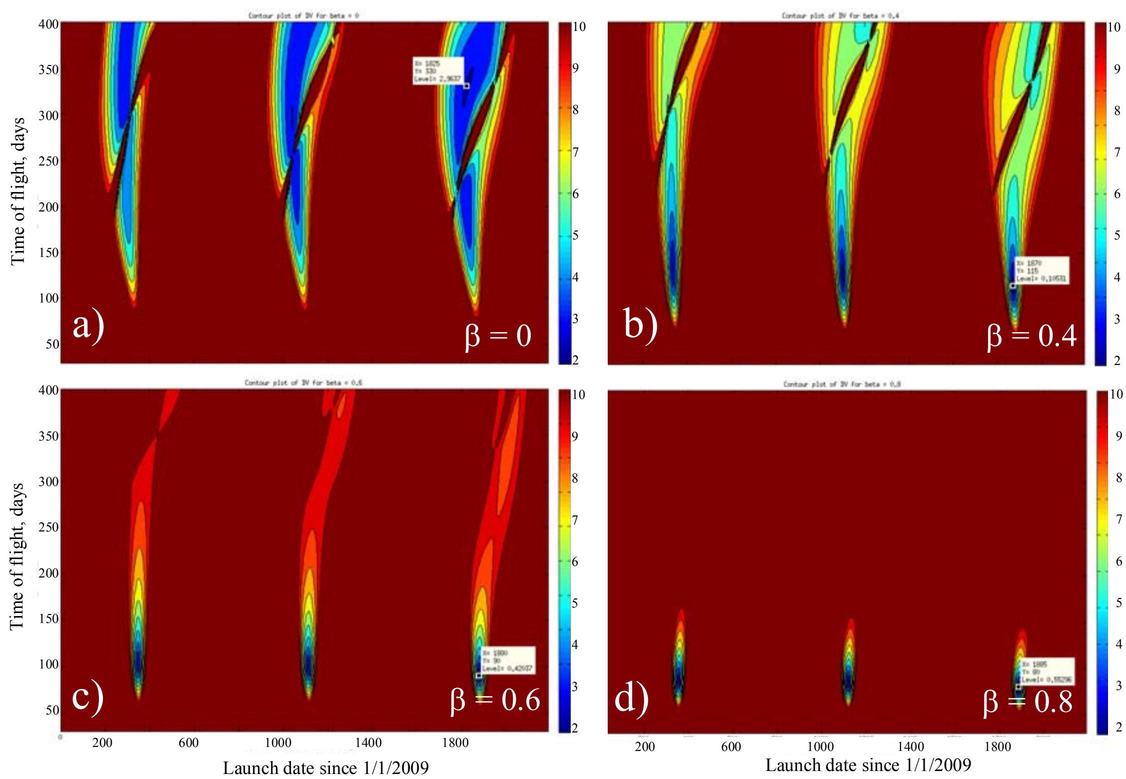


Fig. 3 Contour plots showing Δv as a function of the Time of Flight and the Launch Date for four different values of β.

Finally, in this simulation, we have found a very interesting solution for a transfer orbit with Δv ~0, meaning that all the additional energy needed for the particle to take the transfer orbit from the Earth to Mars is supplied by the radiation pressure. In our idealized case this corresponds to a free transfer to Mars. Such a solution corresponds to a launch date on 2014/02/12 with a time of flight of 119 days and β=0.4. The orbit followed by the nanoparticle is illustrated in Fig. 4. It should be noted that the frame has been distorted vertically in order to appreciate the orbits. Clearly Mars is intercepted at the node as otherwise a zero Δv solution would not exist.

Looking at the results shown in the previous section, we find that for Ag particles of radius $0.25 < R_{pa} < 0.5$ it is possible to design a coating of graphite for which the resulting β equals the optimal one. It is also possible to conclude that for other sizes the graphite coating can not provide such β value.

Earth - Mars Δv≈0 solution

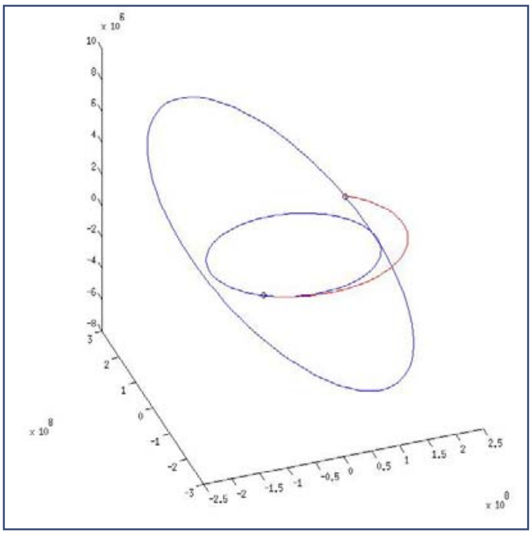


Fig. 4 Transfer orbit described by the nanoparticle departing from an Earth trailing orbit and reaching Mars

5. Conclusions

We propose in this work a technique for controlling the ratio β between the radiation pressure and the gravitational attraction in artificial nanoparticles by applying a properly designed coating.

The results given showed that such a technique can either increase or decrease the β value with respect to the bare particle which will affect directly its dynamics. On the other hand, our approach lacks direct transferability from one material system to another one, meaning that each combination of materials should be studied separately.

We have shown that it is possible to design a transfer mission Earth-Mars with a Δv~0 solution by introducing β as a variable, and thus, for that β value, we can actually design the nanoparticle coating which meets the mission requirements. However, we have also seen that the optimal β value can not be found for certain particle sizes.

In a realistic mission, the Lorentz force, which we neglected in this preliminary work, needs to be taken into account because it would certainly change our results significantly, yet we feel that the methodology we used is of interest and could form the basis for the next steps.

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