Physics, Chemistry, and Dynamics of Interplanetary Dust
ASP Conference Series, Vol. 104, 1996
Bo A. S. Gustafson and Martha S. Hanner (eds.)

Electromagnetic Escape of Dust from the Solar System

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Abstract. Collisions of asteroids and among Zodiacal cloud particles produce large amounts of submicron-sized debris, much of which is immediately ejected from our solar system by electromagnetic forces. We investigate the trajectories of tiny grains started on circular uninclined orbits within the Zodiacal cloud and find that they reach high ecliptic latitudes during the current configuration of the solar magnetic field, perhaps accounting for particles detected by the Ulysses spacecraft at latitudes up to 80°. When the solar magnetic field is reversed, particles are more strongly confined to the ecliptic plane and escape the solar system less readily. Both fluxes and spatial densities of sub-micron sized Zodiacal dust particles vary with time through the dependence of orbital dynamics on the 22-year solar cycle.

1. Introduction

It has long been recognized that solar radiation pressure acting on micron-sized particles in the solar system can cause these grains to escape along hyperbolic trajectories. The acceleration due to radiation pressure can approach and even exceed solar gravity for particles 0.1-0.5μm in radius, but radiation pressure weakens rapidly for smaller particles which do not interact strongly with visible sunlight (Burns *et al.* 1979). Hence very tiny particles cannot be expelled from the solar system by radiation pressure alone. These grains, however, are strongly influenced by the electromagnetic force which arises from the magnetic field embedded in the solar wind. At 2 AU, the strength of the Lorentz force on Zodiacal grains exceeds solar gravity for particles $\lesssim 0.2\mu$m in radius. Electromagnetism causes tiny particles to escape, but along significantly different trajectories than classical beta-micrometeoroids driven purely by radiation pressure. In this paper, we investigate the mechanism of electromagnetic escape from the solar system.

The recent findings of the Ulysses spacecraft provide motivation for our study. After a swing by Jupiter, Ulysses was deflected onto a highly-inclined path which reached ecliptic latitudes of nearly 80°. The spacecraft detected dust particles all along its unique trajectory, even at high latitudes where classical particles responsible for the Zodiacal light are not expected (Baguhl *et al.* 1995). High-latitude particles larger than a few tenths of a micron seem to arrive from a single direction and have been identified as interstellar dust (Grün *et al.* 1993).

Smaller particles, however, come from multiple directions and show only a slight enhancement toward the interstellar upstream direction (see Baguhl *et al.* 1995's Fig. 2). Most of these grains may be interplanetary in origin since interstellar particles of this size have great difficulty penetrating deep into the heliosphere.

2. The Numerical Model

We numerically integrate the equations of motion for spherical grains orbiting the Sun under the influence of gravity and electromagnetism (*cf.* Morfill *et al.* 1986). We restrict ourselves to grains 0.1μm and smaller, for which radiation pressure can be safely neglected, and assume that grains have mass density 2.4 g cm^{-3} and are charged to a constant potential of +5 Volts. The interplanetary magnetic field (IMF), however, is highly-structured and cannot be accurately described by a simple model. When averaged over a solar rotation, however, the IMF is reasonably well represented by Parker's model (Parker 1958, Morfill *et al.* 1986). But using Parker's model implies that the current sheet, a two-dimensional surface which separates regions of inwardly-directed and outwardly-directed magnetic field, is planar. In reality, however, the current sheet is warped in three-dimensions which gives rise to sectors of alternating magnetic polarity observed along Earth's orbit. This sector structure has the important effect of weakening electromagnetic perturbations since the forces felt in adjacent regions cancel to some degree. As a first approximation, therefore, we tilt Parker's magnetic field to the ecliptic by (typically) 30°, and spin it around the Sun's rotation axis with a period of 28 days (the solar rotation rate). This produces two regions of alternating polarity in the ecliptic plane, a situation commonly observed. Finally, we incorporate the solar cycle by simply reversing the sign of the magnetic field every 11 years.

The Lorentz force is given by $q(\mathbf{v} - \mathbf{v}_{sw})/c \times \mathbf{B}$, where $\mathbf{v}$ is the particle's velocity, $\mathbf{v}_{sw} \approx 400$km/s is the solar wind velocity, and $\mathbf{B}$ is the magnetic field. The solar wind velocity is radial, and for most of our orbits, $v_{sw} >> v$. If both the orbit and Parker's magnetic field are tilted by $\lesssim 30°$ then the Lorentz force is primarily normal to the orbit. Particles near the ecliptic plane sense regions of alternating magnetic polarity twice during a solar rotation (*cf.* Hamilton and Burns 1993), while those at high ecliptic latitudes see only a single polarity. Thus the average force on particles close to the ecliptic is much smaller than that on high-latitude grains. For positively-charged particles, the average force is directed away from the ecliptic (defocusing field) during the current solar cycle 23 which lasts from 1991-2002. During the eleven year periods prior to 1991 and after 2002, the force will point toward the ecliptic (focusing field).

For initial conditions, we limit ourselves to circular uninclined orbits. Initial positions are spread out along concentric circles between 0.25 AU and 4.00 AU at intervals of 0.25 AU in distance and 30° in longitude; this approximates the extent of the Zodiacal cloud. We consider particles with different radii between 0.01μm and 0.1μm, tilt angles of 0°, 10°, 30°, and 60° for the magnetic field, and various start times (*i.e.,* phases of the solar cycle).

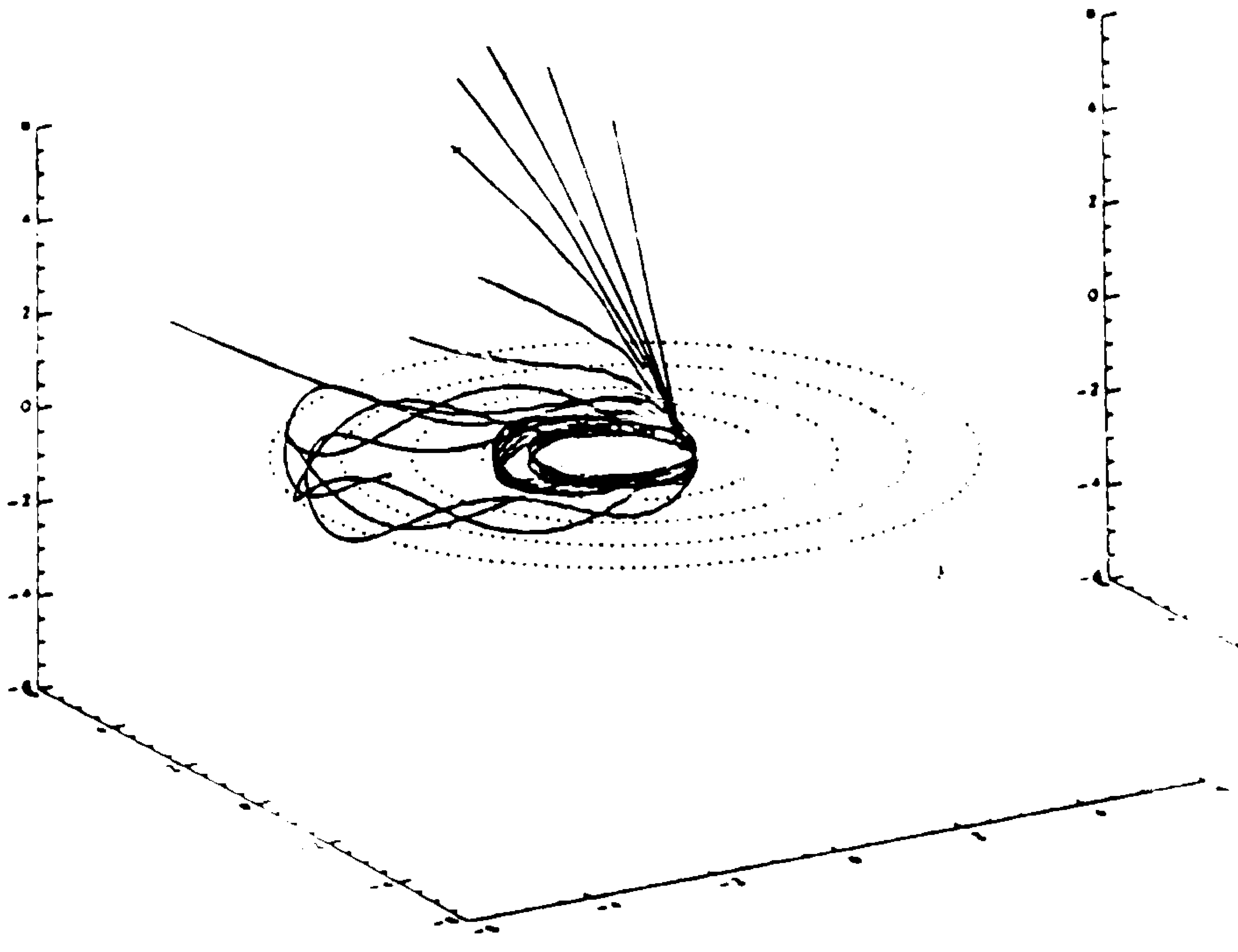

Fig. 1: Orbits in a focusing field (Inner solid oval is Earth's orbit)

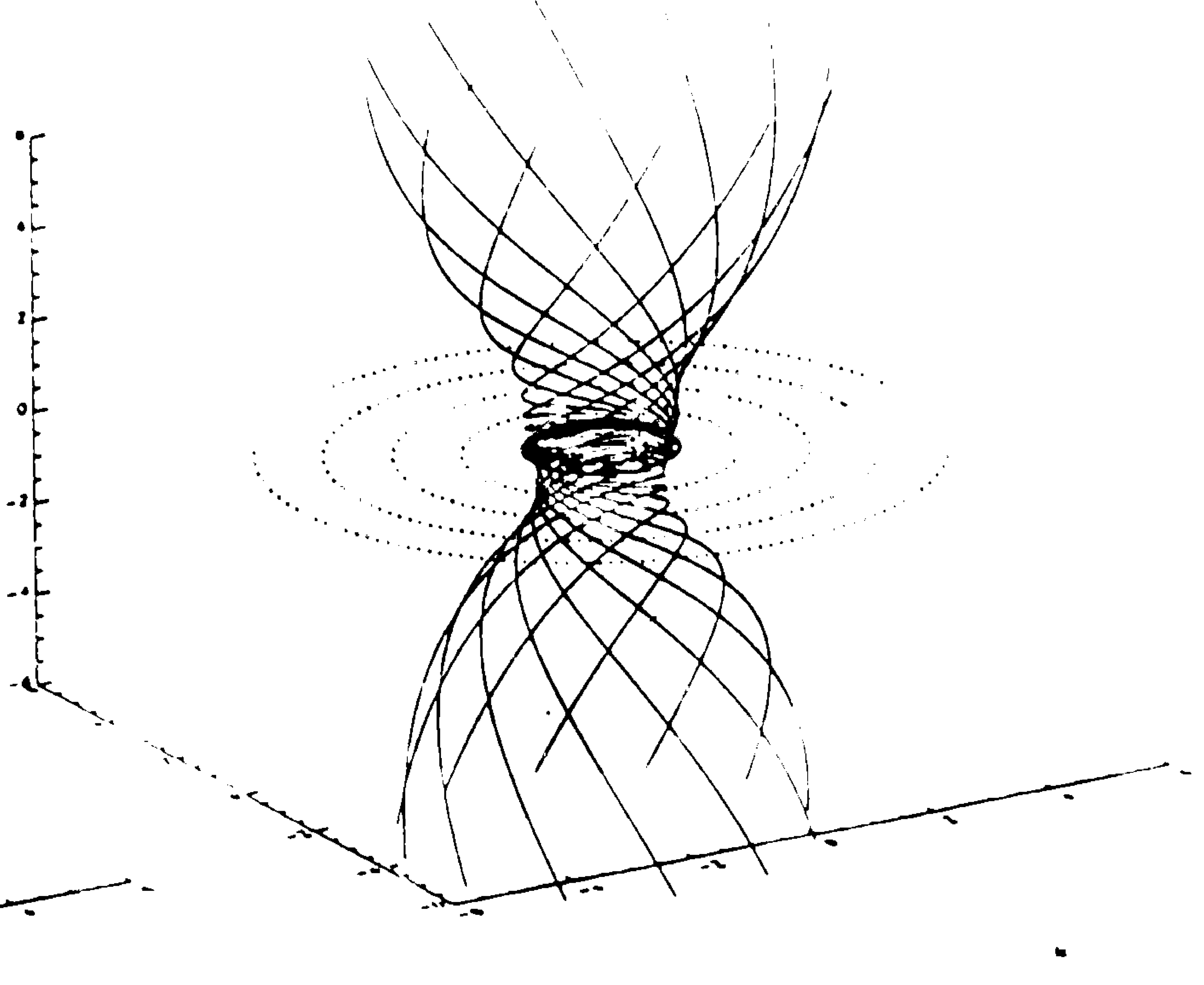

Fig. 2: Orbits in a defocusing field (Outer dashed oval is Jupiter's orbit)

3. Results

Figure 1 shows the fate of eleven particles between 0.01μm and 0.1μm in radius launched on Earth-like orbits in a 30°-tilted Parker field in 1981 (*i.e.*, focusing field). Particles 0.05μm and smaller escaped to 9 AU in less than 1.5 years on trajectories that stayed at low latitudes ($\lesssim 30°$). Grains of radius 0.06μm, 0.08μm and 0.1μm, however, remained bound until the magnetic reversal occurred in 1991; after 1991 (*i.e.*, defocusing field) these escaped in less than two years and attained latitudes in excess of 70°. In addition, the same set of eleven grains started on circles in 1991 all escaped along high-latitude trajectories. This general behavior is expected from our above discussion of the Lorentz force and is also in agreement with results obtained by Morfill *et al.* 1986 with an untilted Parker model (see their Fig. 2).

Interestingly, the *highest* latitudes in the defocusing case are attained by relatively *large* particles, as indicated by Fig. 2 which shows the surface swept out by 0.1μm grains launched at points along a circle at 1 AU. These big grains keep low inclinations for a long time, since the electromagnetic perturbations are initially small due to averaging, and then rapidly shoot up to high latitudes. This effect shows up as an enhanced density near the ecliptic in Fig. 2. That smaller grains escape along paths near the ecliptic plane can be understood by considering gravity as a perturbation on the Lorenz force (for 0.05μm grains near the ecliptic at 1 AU, the Lorentz force is about seven times stronger than gravity). Very tiny particles accelerate rapidly and attain high velocities which, through $\mathbf{v} \times \mathbf{B}$, produces a strong radially-outward force. In short, these grains try to gyrate around the magnetic field which is flowing out radially with the solar wind. The smaller the particle is, the more rapidly it builds up speed in the radial direction. In addition, gravity produces a drift velocity in the vertical direction which is independent of particle size - this is similar to the well-known $\mathbf{E} \times \mathbf{B}$ drift of plasma physics. Since the ratio of these two velocities is related to the change in latitude, it is clear that smaller grains must remain closer to their initial orbital planes.

The behavior of large particles as a function of initial distance is also quite curious. Neglecting radiation pressure, grains of radius $0.15\mu m$ started in 1991 (defocusing field) remain bound for initially circular orbits between 0.75 AU and 1.5 AU but particles both interior and exterior to this disk escape. It is easy to understand the outer boundary - gravity falls off as R^{-2} while the azimuthal magnetic field and the Lorenz force decrease like R^{-1}, where R is heliocentric distance. Hence the Lorentz force is a stronger *perturbation* in the outer solar system. The behavior near the Sun is very complex due to both large orbital speeds which cannot be neglected relative to v_{sw} and electromagnetic resonances. Furthermore, sectors of alternating magnetic polarity are less effective at reducing the electromagnetic perturbation near the Sun since particles move faster and therefore spend more time in a region of one magnetic polarity. A combination of these effects allows $0.15\mu m$ grains close to the Sun to escape.

4. Discussion

The electromagnetic force, modulated by the 22-year solar cycle, causes solar system grains less than about a tenth of a micron in radius to escape along trajectories that can reach high ecliptic latitudes. Even for the extreme case of circular uninclined orbits, tiny dust particles are easily able to reach latitudes in excess of 70° at distances between 2 and 5 AU. Generalizing to inclined and eccentric orbits makes it still simpler for some grains to reach these high latitudes. We believe that these escaping particles have already been detected by the Ulysses spacecraft.

I thank Bo Gustofson and Herb Zook for insightful reviews.

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