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The dynamics of dust particles near the Sun

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RESUMEN

El propósito de este trabajo es estudiar la dinámica de las partículas de polvo (granos) que se encuentran cerca de la corona solar partiendo de un modelo tridimensional que describe la ecuación de movimiento de las partículas tomando en cuenta las fuerzas gravitacional y de Lorentz. Las soluciones del modelo tridimensional proporcionan las superficies de reflexión dentro de las cuales los granos pueden quedar confinados.

Cuando sólo hay movimiento en un plano, las soluciones tridimensionales son reducidas a soluciones bidimensionales.

En particular, se estudia la dinámica de los granos cerca de la corona para dos mínimos solares consecutivos (i.e. antes y después del máximo solar) incluyendo en la ecuación de movimiento la fuerza de presión de radiación.

Las soluciones bidimensionales proporcionan las regiones de confinamiento del polvo alrededor del Sol, así como aquellas regiones en donde el polvo escapa de la heliosfera.

La magnitud tanto de las regiones de confinamiento como de las zonas de escape depende en gran medida del tamaño de los granos, de la relación carga/masa y de la radiación solar.

PALABRAS CLAVE: regiones de confinamiento, superficie de reflexión, relación carga/masa, granos de polvo.

ABSTRACT

A three dimensional (3D) model describes the equation of motion for dust particles taking into account the gravitational and Lorentz forces. Solutions of the model give the reflection surfaces where grains can be confined.

In particular, the dynamics of dust grains near the corona is studied when solar activity is between two consecutive minima (i.e. before and after a maximum), including the radiation pressure into the equation of motion. 2D solutions yield the confinement regions for dust close to the Sun, and for regions where grains can escape from the heliosphere. The size of confinement and escape regions depends basically on grain size, charge/mass ratio and radiation pressure.

KEY WORDS: confinement regions, reflection surface, charge/mass ratio, dust grains.

INTRODUCTION

The dynamics of dust particles in planetary magnetospheres has been studied in the last forty years. Störmer (1957) used two integrals of the equation of motion of relativistic charged particles injected into the terrestrial magnetosphere to characterize their orbits. These integrals were generalized by Artem'ev (1969) to include the effects of gravitational force and Mendis and Axford (1974) included the co-rotational electric field in the gravitoelectrodynamic motion of charged dust in planetary magnetospheres.

We use Mendis and Axford's model to study the dynamics of dust particles (grains) close to the solar corona at 4 solar radii. Such grains were detected during the solar eclipse of June 30, 1973 from infrared observations (Mukai *et al.*, 1974; Mukai and Giese, 1984; Lamy 1974). The equation of motion which describes the dust dynamics will be analyzed in three dimensions (3D). We derive integrals for energy and angular momentum from the 3D equation of charged dust within the heliosphere including both solar gravity and magnetospheric rotation. The solutions may be reduced to two dimensions after some physical considerations.

We will take into account solar radiation pressure to solve the equation of motion in 2D for fine charged dust injected into the heliosphere. The solutions yield the confinement regions of the dust, and of particles injected into the heliosphere at 10 solar radii.

THE MODEL

The solar magnetic field is approximated by a dipole whose axis is parallel or anti-parallel to the spin axis of the Sun for two consecutive minima (Mendis and Axford, 1974, Artem'ev 1979, Horanyi M. 1993, Maravilla *et al*., 1995, 1996). We assume that dust particles are instantly charged at the point of injection and carry a constant electric charge. Otherwise it would be necessary to take into account currents of ions, electrons, secondary electron emission and photoionization picked up by the grains.

In a solar-centric inertial frame (Figure 1) the motion of a dust grain is governed by the equation:

$$m\ddot{\bar{r}} = \frac{Q_0}{c}\left[(\dot{\bar{r}} - \Omega \times \bar{r}) \times \bar{B}\right] - \frac{GMm}{r^3}\bar{r} \quad , \qquad (1)$$

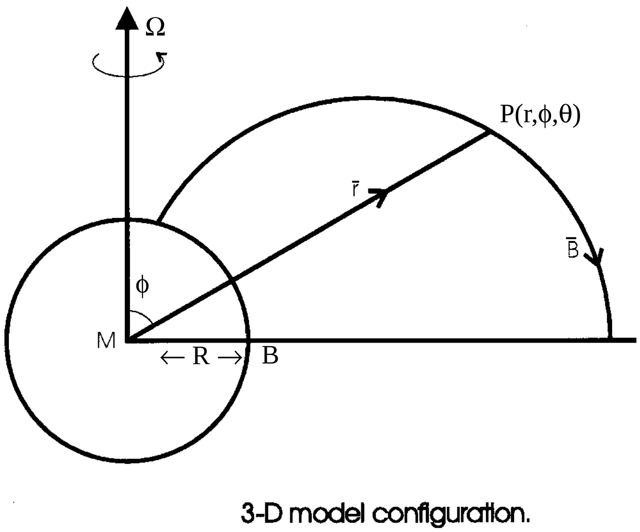

Fig. 1. Three dimensional (3D) model configuration.

where m and Q_0 are the mass and charge of the grain, $\overline{B}$ is the solar magnetic field, c is the velocity of light, G is the gravitational constant, M is the solar mass and Ω is the solar angular velocity.

The vectorial component of the magnetic field in the 3D case is

$$\overline{B} = -2B_0\left(\frac{R}{r}\right)^3 \cos\phi\hat{i}_r - B_0\left(\frac{R}{r}\right)^3 \sin\phi\hat{i}_\phi \quad , \qquad (2)$$

where B_0 is the solar surface magnetic field at the equator and $\hat{i}_r$ and $\hat{i}_\phi$ are the radial and transverse unit vectors respectively.

Taking the dot product of (1) with $\dot{\bar{r}}$, we get

$$\frac{d}{dt}\left(\frac{1}{2}v^2\right) = A\Omega\frac{d}{dt}\left(\frac{\sin^2\phi}{r}\right) - \frac{GM}{r^2}\frac{dr}{dt} \ , \qquad (3)$$

where A=-$\frac{Q_0 B_0 R^3}{mc}$ and $v^2 = \bar{v}\cdot\bar{v}$. The suffix 'o' represents initial conditions. R is the solar radius and v_0 is the speed of the grain at the point of injection.

Taking the dot product of (1) with $\hat{i}_\theta$, the unit vector in the azimuthal direction, we find

$$\frac{d}{dt}\left(r^2\sin^2\phi\dot{\theta}\right) = -\frac{A}{r^2}\left(\sin^2\phi\dot{r} - 2r\sin\phi\cos\phi\dot{\phi}\right) = \frac{d}{dt}\left(\frac{A\sin^2\phi}{r}\right). \qquad (4)$$

Integrating equation (3) between the point of injection $\bar{r}_0$ and $\bar{r}$, we obtain the energy equation. Considering that r=r_0 and $v^2 = v_0^2 = \frac{KGM}{r_0}$ at the point of injection, the energy equation is expressed by

$$v^2 - \frac{2A\Omega\sin^2\phi}{r} - \frac{2GM}{r} = \frac{KGM}{r_0} - \frac{2A\Omega\sin^2\phi_0}{r_0} - \frac{2GM}{r_0} \ . \qquad (5)$$

Thus

$$v^2 = v_0^2 + 2A\Omega\left(\frac{\sin^2\phi}{r} - \frac{\sin^2\phi_0}{r_0}\right) - 2GM\left(\frac{1}{r} - \frac{1}{r_0}\right). \qquad (6)$$

Integrating equation (4) between r_0 and r and assuming that

$$r\sin\phi(r\sin\phi\theta) = \frac{A\sin^2\phi}{r} + k'$$

where

$$k = \frac{A\sin^2\phi}{r} + k' \ ,$$

$$k_0 = \frac{A\sin^2\phi_0}{r_0} + k' \ ,$$

$$k' = r^2\sin^2\phi\theta - \frac{A\sin^2\phi}{r} = constant$$

and $k(= r^2\sin^2\phi\dot{\theta})$ is the specific angular momentum of the grains about the dipole axis and k_0 is the angular momentum at the point of injection, the equation for the angular momentum is

$$k - k_0 = \frac{A\sin^2\phi}{r} - \frac{A\sin^2\phi_0}{r} .$$

Thus

$$k = k_0 + A\left(\frac{\sin^2\phi}{r} - \frac{\sin^2\phi_0}{r_0}\right) . \qquad (7)$$

If

$$x = \frac{r}{r_0} \qquad (8)$$

and

$$y = \frac{\sin^2\phi}{\sin^2\phi_0} \ , \qquad (9)$$

the energy equation becomes

$$v^2 = \frac{KGM}{r_0} - \frac{2GM}{r_0}\left(1 - \frac{1}{x}\right) - 2A\Omega\frac{\sin^2\phi_0}{r_0}\left(1 - \frac{y}{x}\right) \qquad (10)$$

and organizing all terms, we finally obtain

$$v^2 = \frac{KGM_\oplus}{r_0} - \frac{2GM}{r_0}\left(\frac{x-1}{x}\right) - 2A\Omega\frac{\sin^2\phi_0}{r_0}\left(\frac{x-y}{x}\right). \quad (11)$$

From equation (7), the angular momentum is expressed by

$$k = k_0 - \frac{A\sin^2\phi_0}{r_0}\left(1-\frac{y}{x}\right); \quad (12)$$

thus

$$k = k_0 - \frac{A\sin^2\phi_0}{r_0}\left(\frac{x-y}{x}\right) \quad (13)$$

where

$$v_\theta = \frac{k}{r\sin\phi} \quad (14)$$

is the azimuthal velocity. Substituting equation (13) into (14), we obtain

$$v_\theta^2 = \frac{1}{x^2y}\left[\frac{k_0^2}{r_0^2\sin^2\phi_0} - \frac{2Ak_0}{r_0^3}\left(\frac{x-y}{x}\right) + \frac{A^2\sin^2\phi_0}{r_0^4}\left(\frac{x-y}{x}\right)^2\right]. \quad (15)$$

From equations (6) and (7) and noting that

$$v^2 \geq v_\theta^2\left(\frac{k^2}{r^2\sin^2\phi}\right) \quad (16)$$

we obtain

$$\frac{KGM}{r_0} - \frac{2GM}{r_0}\left(\frac{x-1}{x}\right) - 2A\Omega\frac{\sin^2\phi_0}{r_0}\left(\frac{x-y}{x}\right) \geq \frac{1}{x^2y}\left[\frac{k_0^2}{r_0^2\sin^2\phi_0} - \frac{2Ak_0}{r_0^3}\left(\frac{x-y}{x}\right) + \frac{A^2\sin^2\phi_0}{r_0^4}\left(\frac{x-y}{x}\right)^2\right]. \quad (17)$$

In equation (17), L_0 is the magnetic parameter defined as

$$L_0 = \frac{r_0}{R} \quad , \quad (18)$$

and

$$p = \frac{A\Omega}{GM_\oplus} \quad . \quad (19)$$

Thus we obtain

$$\frac{1}{L_0R}\left[\frac{x(K-2)+2}{x}\right] - 2p\frac{\sin^2\phi_0}{L_0R}\left(\frac{x-y}{x}\right) \geq \left[\frac{k_0^2}{GML_0^2R^2\sin^2\phi_0} - \frac{2pk_0}{\Omega L_0^3R^3}\left(\frac{x-y}{x}\right) + p^2\frac{GM}{\Omega^2}\frac{\sin^2\phi_0}{L_0^4R^4}\left(\frac{x-y}{x}\right)^2\right]. \quad (20)$$

Rewriting this expression we obtain

$$xy\left[\{x(K-2)+2\} - 2(x-y)p\sin^2\phi_0\right] \geq \frac{k_0^2}{GML_0R\sin^2\phi_0} - \frac{2pk_0}{\Omega L_0^2R^2}\left(\frac{x-y}{x}\right) + p^2\frac{GM}{\Omega^2}\frac{\sin^2\phi_0}{L_0^3R^3}\left(\frac{x-y}{x}\right)^2 . \quad (21)$$

Multiplying by x^2 and noting that

$$k_0 = (r_0\sin\phi_0)v_{\theta,0},$$

$$|k_0| \leq r_0\sin\phi_0 v_0 = r_0\sin\phi_0\sqrt{\frac{KGM}{r_0}} = \sin\phi_0\sqrt{KGMRL_0},$$

and

$$k_0 = \beta\sin\phi_0\sqrt{KGMRL_0} \text{ with } |\beta| \leq 1 .$$

Equation (21) can be written

$$x^3y\left[\{x(K-2)+2\} - 2(x-y)p\sin^2\phi_0\right] \geq K\beta^2x^2 - 2px(x-y)\frac{\beta\sin\phi_0}{\Omega L_0^2R^2}\sqrt{KGMRL_0} + p^2\frac{GM}{\Omega^2}\frac{\sin^2\phi_0}{L_0^3R^3}(x-y)^2 \geq K\beta^2x^2 - 2px(x-y)\beta\sin\phi_0\sqrt{\frac{KGM}{\Omega^2R^3L_0^3}} + p\sin^2\phi_0\frac{GM}{\Omega^2R^3L_0^3}(x-y)^2 . \quad (22)$$

Let us define a parameter $|\alpha|$ as the relationship between the gravitational constant G, the solar mass M, the solar angular velocity Ω and the solar radius R

$$\alpha^2 = \frac{GM}{\Omega^2R^3} . \quad (23)$$

Thus

$$x^3y\left[\{x(K-2)+2\} - 2(x-y)p\sin^2\phi_0\right] \geq$$

$$K\beta^2x^2 - 2x(x-y)\beta\sqrt{\frac{K}{L_0^3}}\alpha\sin\phi_0 p + p^2(x-y)^2\sin^2\phi_0\,\frac{\alpha^2}{L_0^3}. \quad (24)$$

In terms of y, this yields

$$\sin^2\phi_0\left(p^2\frac{\alpha^2}{L_0^3} - 2px^3\right)y^2 - \left[2x\sin^2\phi_0 p^2\frac{\alpha^2}{L_0^3} - 2x\beta\alpha\sqrt{\frac{K}{L_0^3}}\sin\phi_0 p + x^4(K-2) + 2x^3 - 2x^4 p\sin^2\phi_0\right]y + \left[K\beta^2x^2 - 2x^2\beta\alpha\sqrt{\frac{K}{L_0^3}}\sin\phi_0 p + p^2x^2\sin^2\phi_0\frac{\alpha^2}{L_0^3}\right] \le 0 \;. \quad (25)$$

From equation (25), we obtain a quadratic equation expressed in dimensionless quantities:

$$F(x,y,p;k,\beta,\phi_0,L_0;\alpha) = \sin^2\phi_0\left(\frac{p^2\alpha^2}{L_0^2} - 2px^3\right)y^2 - \left(\frac{2xp^2\alpha\sin^2\phi}{L_0^3} - 2x\beta\alpha\left(\frac{K}{L_0^3}\right)^{1/2}p\sin^2\phi_0 - x^4(K-2) + 2x^3 - 2x^4p\sin^2\phi_0\right)y + \left(K\beta^2x^2 - 2x^2\beta\alpha\left(\frac{K}{L_0^3}\right)^{1/2}p\sin\phi_0 + p^2x^2\alpha^2\frac{\sin^2\phi_0}{L_0^3}\right) \le 0 \,, \quad (26)$$

where K and β are defined through $v_0 = \sqrt{\frac{KGM}{r_0}}$ and $k_0 = \beta(r_0 \sin\phi_0)v_0$ (where $|\beta| \le 1$).

Thus $F(x,y,p;\, K,\beta,\phi_0,L_0;\alpha)=0$ taken at specific values of the parameters p, K, β, ϕ_0 and L_0 is the equation of the reflection surface (i.e. where $v=v_\theta$ so that $v_r=0=v_\theta$). This equation is quadratic in y, which is convenient to discuss the region occupied by the allowed orbits in the x-y plane. This is given by $y_1 \le y \le y_2$, where y_1 and y_2 are the roots of $F=0$. For the special case when the particle is projected on the meridional plane with the local gravitational speed $K=2$, the 3D equation is reduced to two dimensions as

$$\sin^2\phi_0\left(\frac{p^2\alpha^2}{L_0^3} - 2px^3\right)y^2 - \left(2xp^2\frac{\alpha^2}{L_0^3}\sin^2\phi_0 + 2x^3 - 2x^4p\sin^2\phi_0\right)y + p^2x^2\frac{\alpha^2}{L_0^3}\sin^2\phi_0 \le 0 \;, \quad (27)$$

with the solutions

$$p_1(y) \le y \le p_2(y) \;. \quad (28)$$

DUST GRAINS IN THE INNERMOST REGIONS OF THE HELIOSPHERE

In addition to electromagnetic and gravitational forces we now include radiation pressure. The equation of motion is

$$m\ddot{r} = \frac{Q_0}{c}\left[\left(\dot{\bar{r}} - \Omega\times\bar{r}\right)\times\bar{B}\right] - \frac{GMm}{r^3}\bar{r} + \frac{Q_{pr}}{c}\frac{L_\circ a^2}{4}\frac{\bar{r}}{r^3} \;, \quad (29)$$

where the last term is the radiation pressure, m is the grain mass, c is the light velocity, G is the gravitational constant, M is the solar mass, Q_{pr} is the radiation pressure coefficient, $L_\circ$ is the solar luminosity, ρ is the density and a is the grain radius.

Equation (29) describes the situation of dust grains injected at L_0=10 into the heliosphere considering two consecutive solar minima (1 and 2), before and after a solar maximum (Figures 2 a, b, c). Dust particles are moving in two dimensions (Figure 3). We select L_0=10 in order to find whether dust particles from the interplanetary medium can be trapped by the Sun near the corona.

If the solar magnetic field is a dipole, $\bar{B} = -B_0\left(\frac{R}{r}\right)^3\hat{i}_z$ for solar minimum 1 and $\bar{B} = B_0\left(\frac{R}{r}\right)^3\hat{i}_z$ for solar minimum 2 (22 years later) and $\bar{\Omega} = \Omega\hat{i}_z$. Then

$$\ddot{r} - r\dot{\phi}^2 = \frac{A(\dot{\phi}-\Omega) - G'M}{r^2} \text{ for solar minimum 1} \quad (30)$$

and

$$\ddot{r} - r\dot{\phi}^2 = \frac{A(\Omega-\dot{\phi}) - G'M}{r^2} \text{ for solar minimum 2 ,} \quad (31)$$

where

$$\frac{d}{dt}(r^2\dot{\phi}) = -A\frac{\dot{r}}{r^2} \,,$$

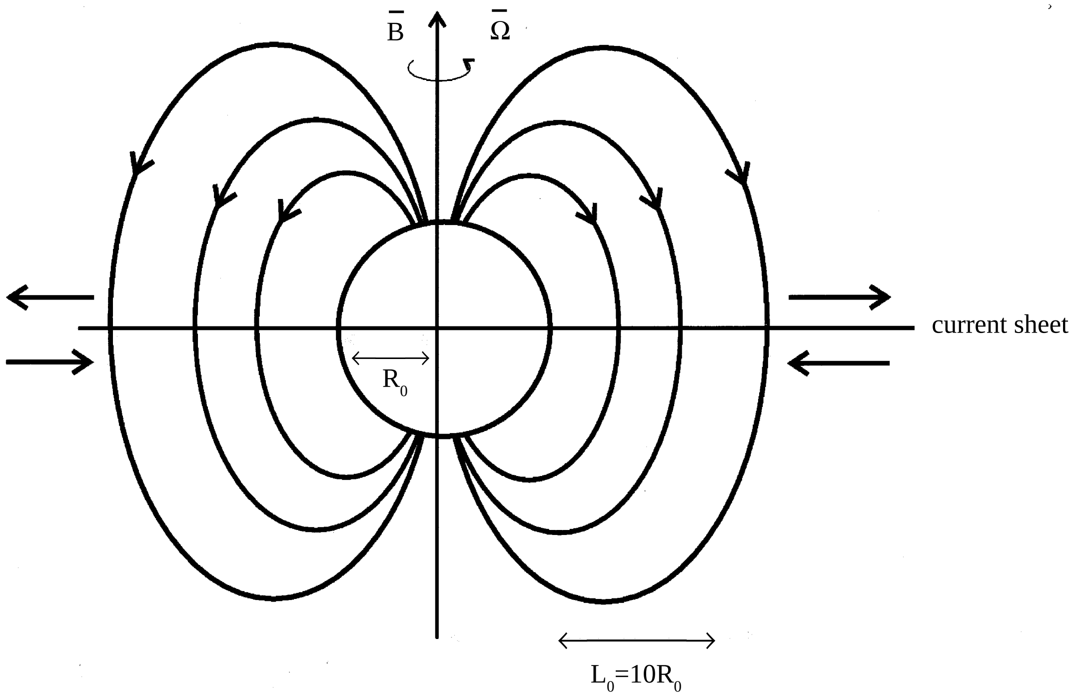

Fig. 2a. Magnetic field configuration at solar minimum 1.

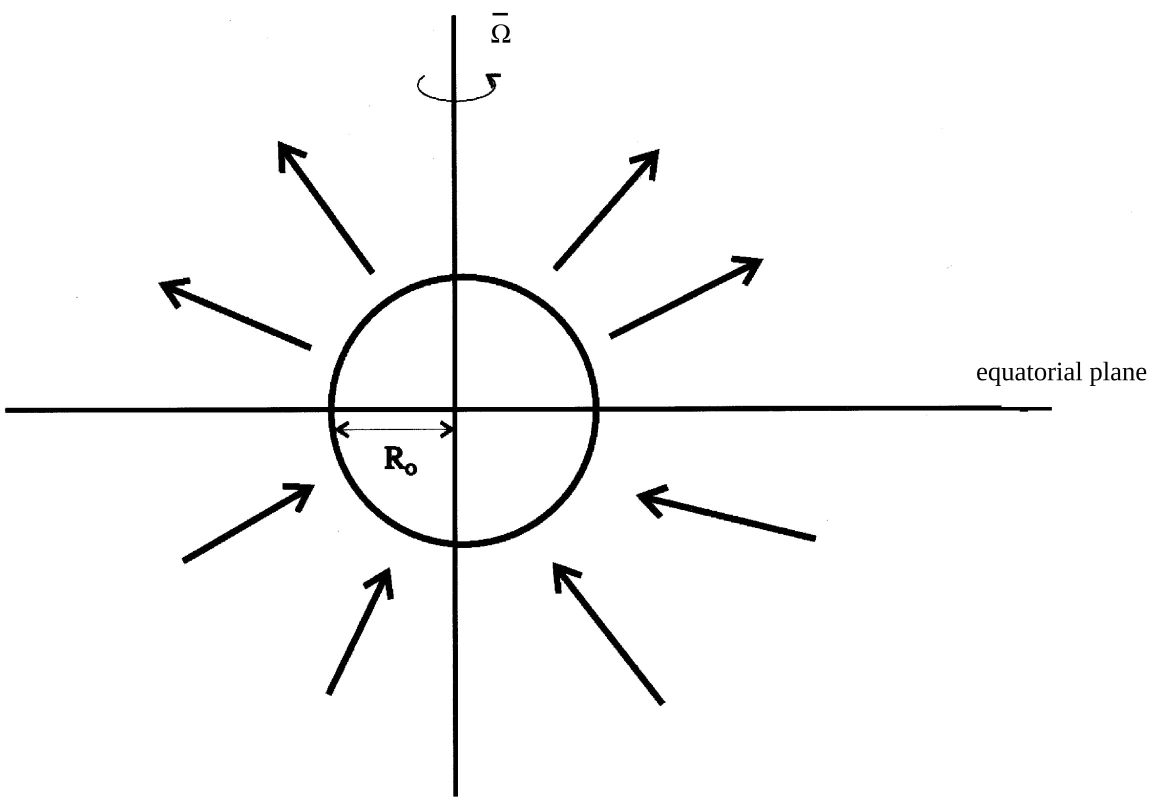

Fig. 2b. Magnetic field configuration at solar minimum.

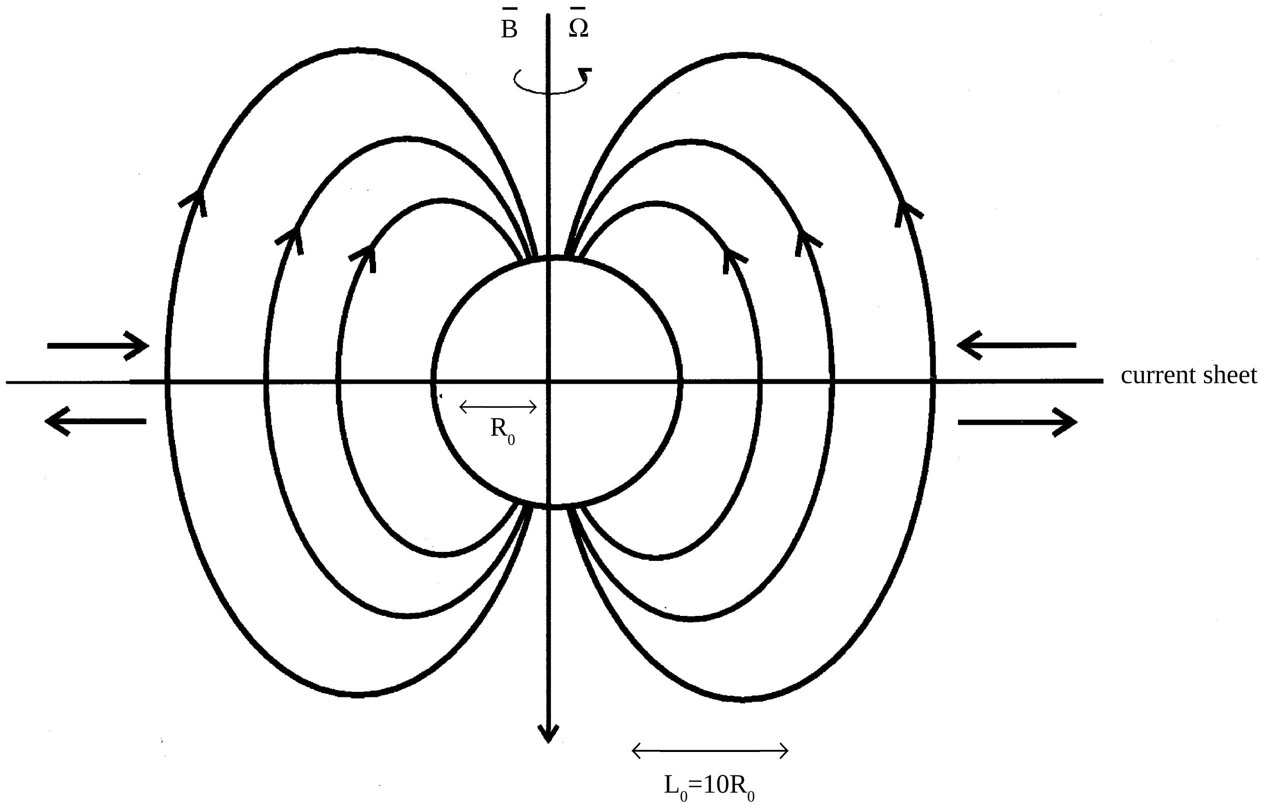

Fig. 2c. Magnetic field configuration at solar maximum 2.

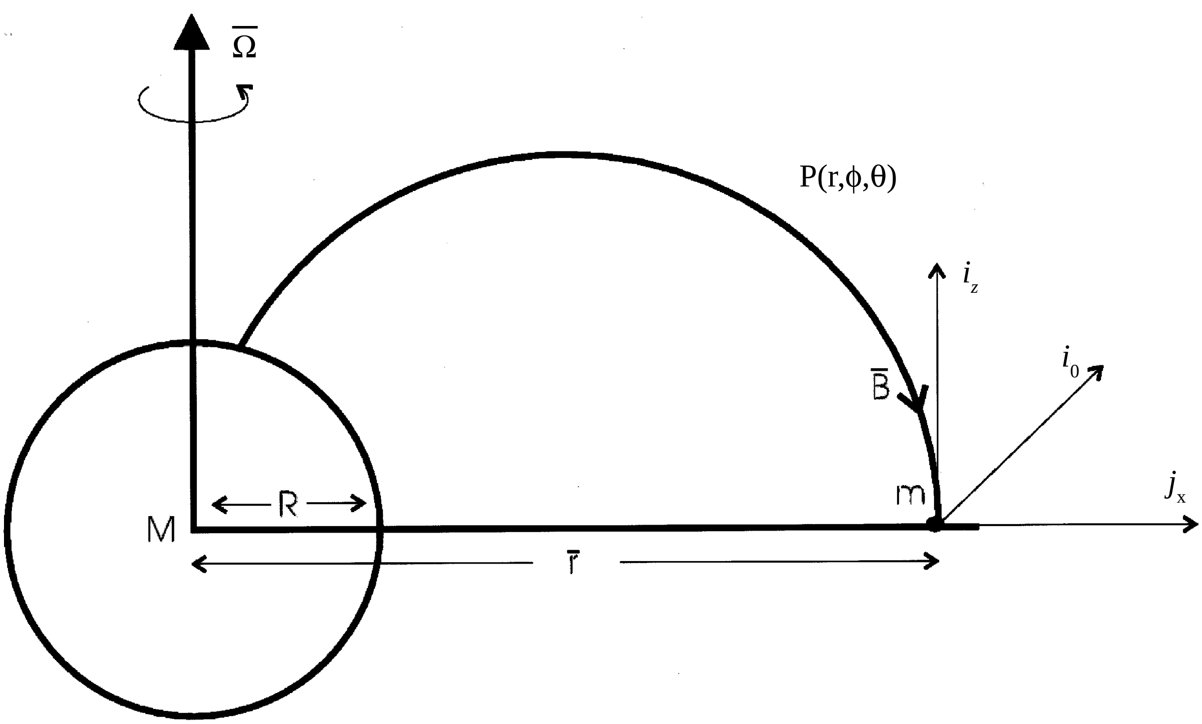

Fig. 3. Two dimensional (2D) model configuration.

$$A = -\frac{Q_0 B_0 R^3}{mc}$$

and

$$G' = G\left(1 - \frac{3Q_{pr} L_\circ}{16\pi G M \rho c}\frac{1}{a}\right). \qquad (32)$$

If grains are emitted at a distance r_0 with speed $v_0 = \sqrt{\frac{KG'M}{r_0}}$ at an angle ϕ_0 to the radial direction and if they are instantly charged to a value Q_0, we obtain a 2-D solution (Figure 3) from (30) and (31) as follows:

$$F(p, y; L_0, \phi_0, K) = p^2 - \frac{2L_0^3}{\alpha^2}\frac{y}{1-y}\left(\pm y^2 \mp \alpha\left(\frac{K}{L_0^3}\right)^{1/2}\sin\phi_0\right)p$$

$$-\frac{L_0^3}{\alpha^2}\frac{y^2}{(1-y)^2}\left(K\left(y^2 - \sin^2\phi_0\right) + 2y(1-y)\right) \le 0 \qquad (33)$$

for solar minima 1 and 2 respectively. The parameters p, L_0 and α' are defined as follows:

$$p = \frac{A\Omega}{G'M}$$

$$L_0 = \frac{r_0}{R}$$

$$\alpha'^2 = \frac{G'M}{\Omega^2 R^3}.$$

We solve the quadratic equations for grains approaching in the radial direction to r_0=10R and we consider the regions of p-y space where real orbits are possible. In this case,

$$p = -\frac{\beta}{G}(a^2 - \alpha' a)^{-1}$$

where

$$\beta = \frac{3\phi B_0 R^3 \Omega}{4\pi\rho c M} = 3.869\times10^{-7}$$

and

$$\alpha' = \frac{3Q_{pr}L_0}{16\pi G M\rho} = 5.74\times10^{-5}.$$

RESULTS AND DISCUSSION

When L_0, ϕ_0 and K are fixed, then for a given value of y, the equation $F(p,y; L_0, \phi_0, K)=0$ is quadratic in the parameter p. When p is real, p must lie between two real roots $p_1(y)$ and $p_2(y)$ of this equation. This enables one to find the regions of p - y space where real roots are possible.

When K=2 and ϕ_0=0 we obtain solutions for solar minimum 1 and solar minimum 2 as follows:

$$p^2 - \frac{2L_0^3}{\alpha^2}\frac{y^3}{1-y}p - \frac{2L_0^3}{\alpha^2}\frac{y^3}{(1-y)^2} = \left(p - p_1(y)\right)\left(p - p_2(y)\right) \le 0 \qquad (34)$$

and the physically allowed regions for dust orbits are

$$p^2(y) \le p \le p_1(y). \qquad (35)$$

Taking different values of a, we may find the solutions $p_1(y)$ and $p_2(y)$ shown in Figure 4 (a, b) for a=1μm, in Figure 5 (a, b) for a=5μm and in Figure 6 (a, b) for a=0.6μm.

The physically allowed region for the orbits $p_2(y) \le p \le p_1(y)$ is shown as a lightly shaded area. The lower non-shaded region also complies with $p_2(y) \le p \le p_1(y)$, but this region is physically spurious because the grain cannot access it at y=1.

Thus as a decreases, more grains can escape from the heliosphere; otherwise they are trapped by Lorentz and gravitational forces.

Note that the shaded region grows substantially as the grain radius decreases. In this case, trapped grains remain in a narrow region where they are confined by magnetic field lines because they evolve around these lines.

There is a critical radius when G'=0; in this case a_c = 0.574 μm. When G'<0, dust grains are ejected by radiation pressure from the heliosphere.

CONCLUSIONS

We derive two integrals of the general 3-D gravitoelectrodynamic motion of charged dust within the co-rotating region of a planetary magnetosphere to study the case of dust grains injected into the heliosphere.

Our approach requires the use of several aproximations, including the assumption that the magnetic moment and the spin vectors are strictly parallel and that the grain charge is constant.

We construct the spatial regions where the grains are confined, at least initially, before evolutionary effects take over.

A particular case of our 3-D model is the 2-D model. This model was used to derive the confinement regions where dust can be trapped around the Sun.

The 2-D model has now been modified in order to include solar radiation pressure. This model was used to study

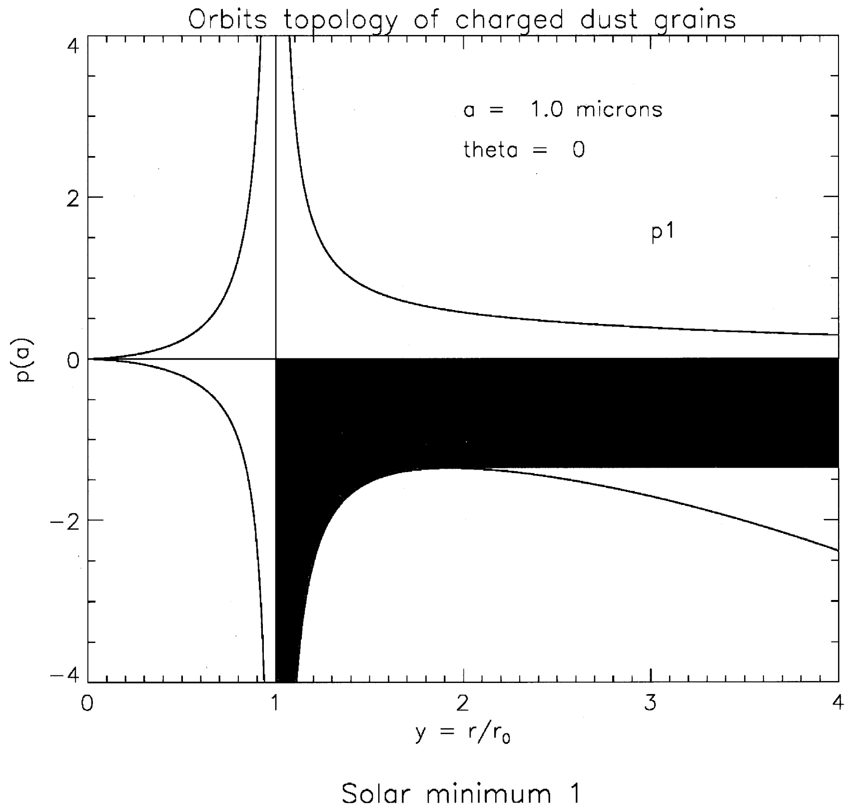

Fig. 4a. Orbits of charged dust grains launched at L_0=10. The lightly shaded region is the region in the *p-y* plane where real orbits can lie. The point of launch is given by *y*=1 at minimum 1. Positively charged grains correspond to *p*<0. The size of the injected grains is 1.0 micron.

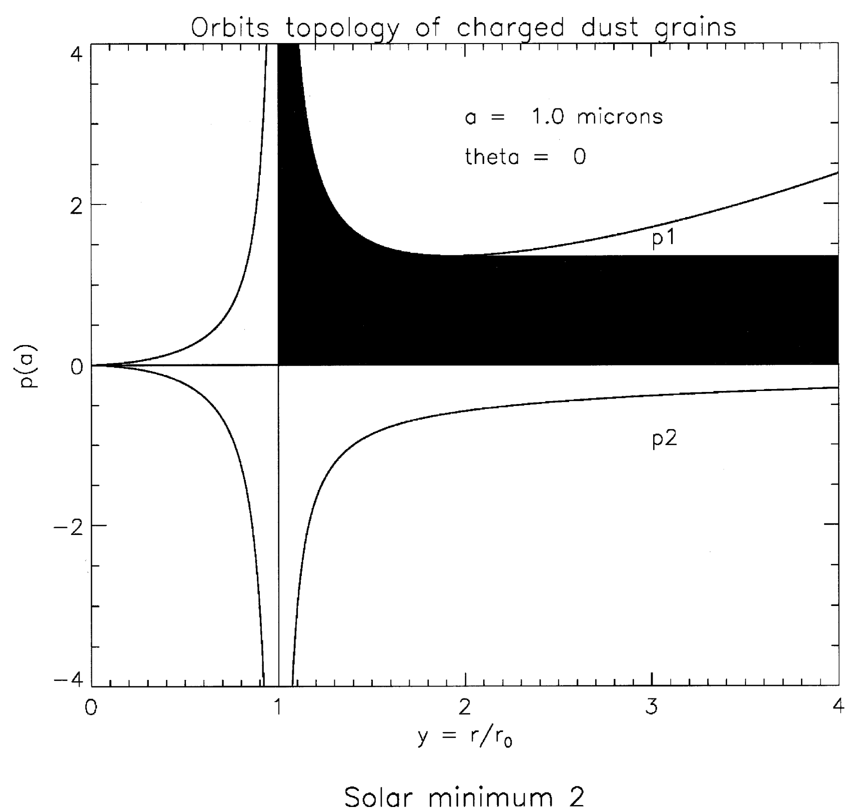

Fig. 4b. Same as Fig. 4a except that grains are launched when the solar activity is at minimum 2.

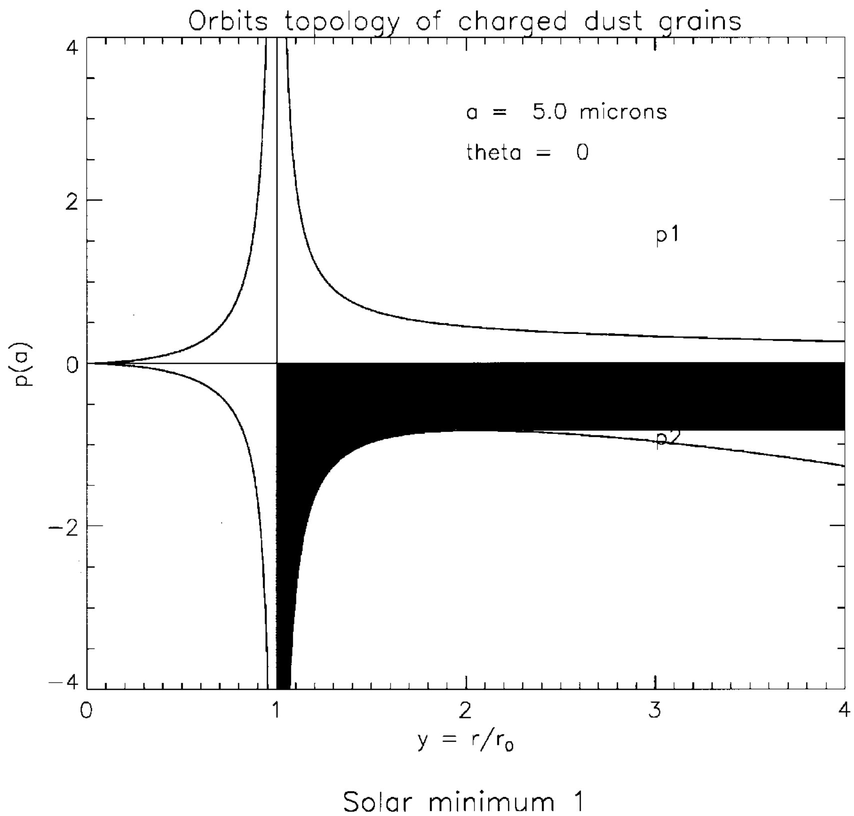

Fig. 5a. Same as Fig. 4a except that the size of the injected grains is 5.0 microns.

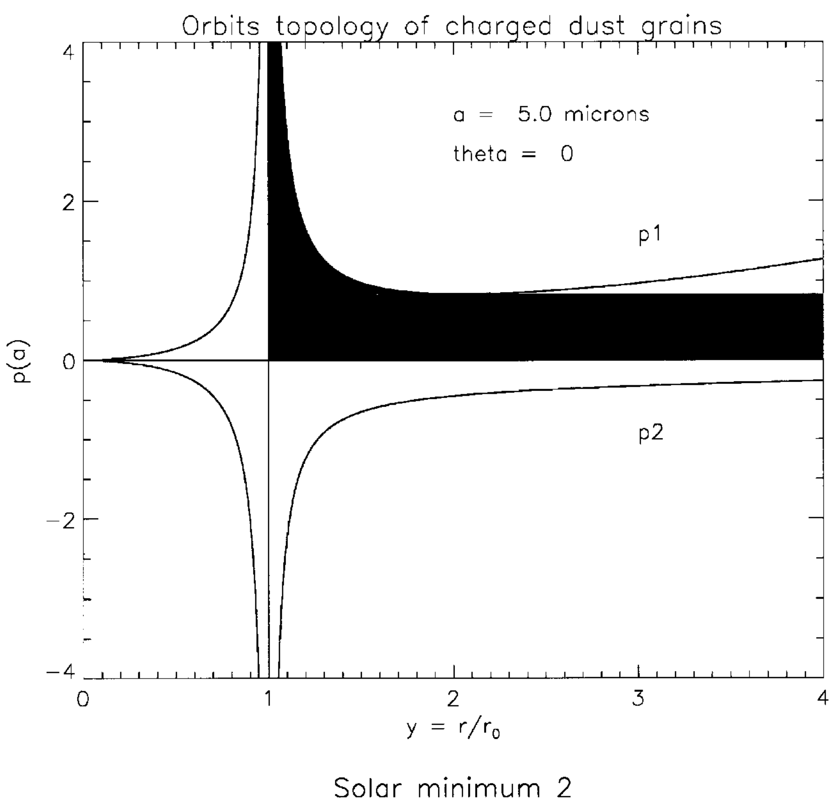

Fig. 5b. Same as Fig. 4b except that the size of the grains is 5.0 microns.

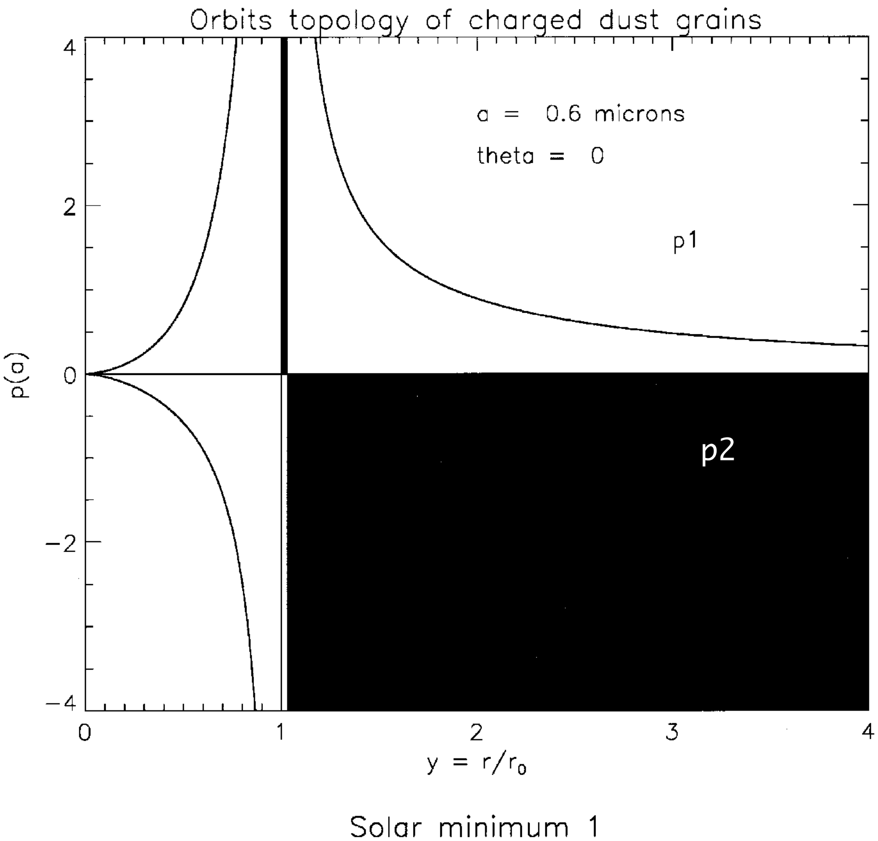

Fig. 6a. Same as Fig. 5a except that the size of injected grains is 0.6 microns.

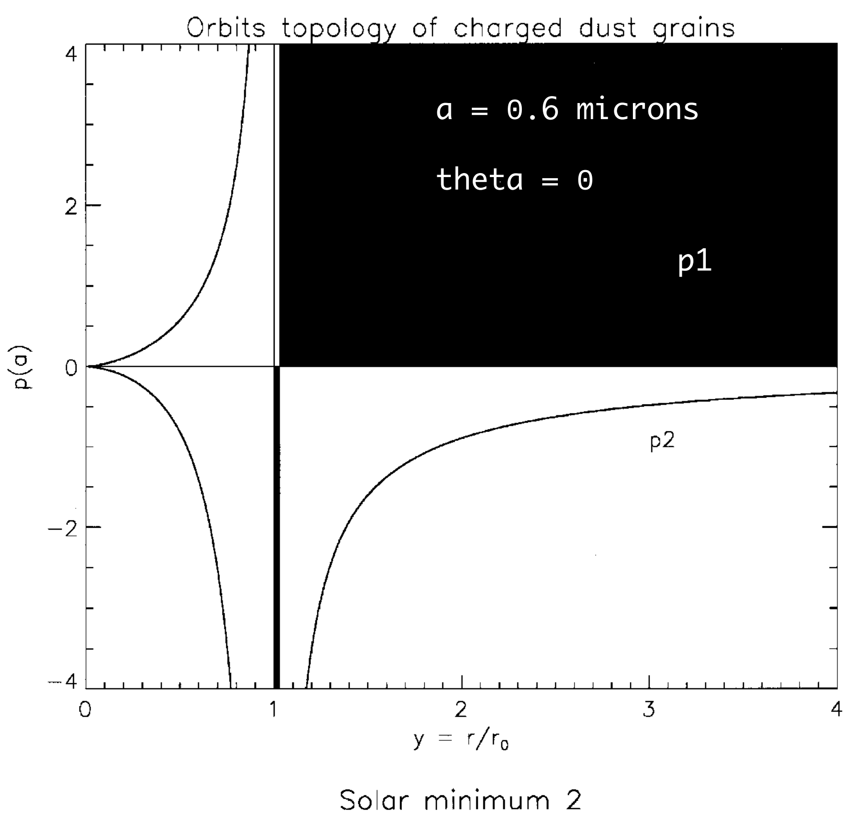

Fig. 6b. Same as Fig. 5b except that the size of the grains is 0.6 microns.

interplanetary dust particles that are close to the Sun, including the cyclical change of the solar magnetic field. We find that there is a critical radius for the grains (G'=0), such that grains are dominated by radiation pressure when G'< 0.

The effect of sublimation will be included in a future model.

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