Revista Mexicana de Astronomía y Astrofísica, **50**, 341–347 (2014)

THE SATURNIAN G RING: A SHORT NOTE ABOUT ITS FORMATION

D. Maravilla and J. L. Leal-Herrera
Departamento de Ciencias Espaciales, Instituto de Geofísica, UNAM, Mexico

Received March 21 2014; accepted August 18 2014

RESUMEN

En este trabajo se estudia la formación del anillo G de Saturno considerando que el satélite Egeón es la fuente de partículas de polvo. El polvo que forma el anillo se produce por impactos entre los micrometeoroides interplanetarios que ingresan en la magnetósfera Saturniana y la superficie de Egeón. Para explicar cómo se forma el anillo se usa un modelo gravito-electrodinámico suponiendo que las fuerzas gravitacional y electromagnética son las únicas fuerzas que modulan el comportamiento dinámico de las partículas de polvo. Las soluciones del modelo muestran que existen regímenes de confinamiento (captura) así como regímenes de escape de polvo en la vecindad de Egeón. Los regímenes de confinamiento contienen partículas de polvo de tamaño micro y nanométrico que forman una estructura anular alrededor de Saturno. El tamaño del radio de Larmor de las partículas micrométricas confinadas coincide con la extensión radial del anillo G.

ABSTRACT

In this paper we examine the formation of the Saturnian G ring by considering the motion of dust launched from the surface of Aegaeon. Those particles are ejected from the satellite surface by impacts between the interplanetary meteoroids and the satellite. The gravito-electrodynamic model we use involves only two forces (gravitational and Lorentz), and its solutions show the confinement (capture) and the escape regimes of dust in the vicinity of Aegaeon. The results for the captured dust size show sub-micron and nanometric dust populations. In addition, the Larmor radius of captured dust particles near Aegaeon was calculated and the results are in good agreement with the G-ring radial extent.

Key Words: meteorites, meteors, meteoroids — planets and satellites: individual (Saturn) — planets and satellites: rings

1. INTRODUCTION

The Saturnian G-ring was first detected by the spacecraft Pioneer 11 in 1979; its existence was confirmed by the Voyager spacecraft (Throop & Esposito 1998) and it has been studied by the Cassini mission in the last decades. This tenuous ring has a radial extent of $\approx 1.0\times 10^4$ km, and it has an inner boundary located at 1.65×10^5 km from the center of the planet (Hedman et al. 2007; Porco et al. 2007; Horányi et al. 2009). The dust of this ring is probably provided by the moonlet Aegaeon, which is prolate and shows a reddish dirty surface maybe contaminated by comets or meteoroids. Aegaeon is embedded in a bright arc centered on the satellite's orbit (Hedman et al. 2007, 2009a,b; Horányi et al. 2009); which is likely confined by the 7:6 corotation eccentricity resonance with the satellite Mimas (Hedman et al. 2007).

Recent work has examined the formation of the G ring and its various structures (Hedman et al. 2010). In this work an analytical model is used to examine the formation of the G-ring in order to look for confinement regimes (capture) of dust particles, ejected from the Aegaeon's surface, that remain in the vicinity of the satellite. We consider dust particles coming from meteoroid impacts on the satellite surface.

The results show that dust particles in the confinement regimes could be part of G-ring dust populations. For completeness the Larmor radii of trapped particles have also been calculated, and their size is comparable to the G-ring's radial extent.

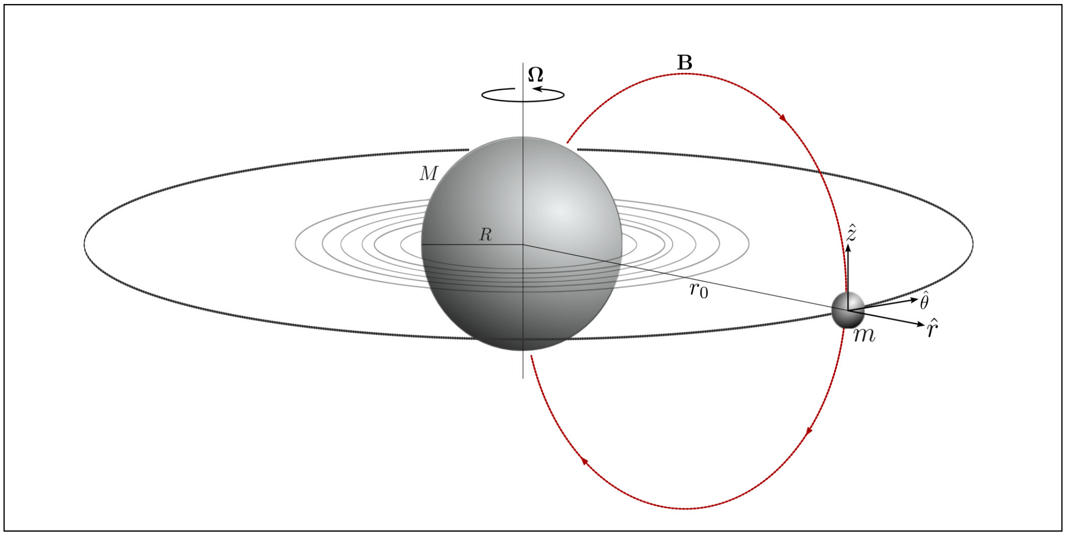

Fig. 1. The geometric configuration of the model.

2. THE ANALYTICAL MODEL

We use a gravito-electrodynamic model created by Mendis and Axford in order to study the dynamics of charged micrometeoroids by planetary magnetospheres (Axford & Mendis 1974; Mendis et al. 1982, 1983; Northrop & Hill 1982; Hamilton 1993; Schaffer & Burns 1994; Maravilla et al. 1995a,b, 1996; Horányi 2000; Mitchell et al. 2003; Maravilla & Flandes 2005; Hsu et al. 2012; Jontof-Hutter & Hamilton 2012). Starting from this model, dust particles ejected from the Aegaeon surface describe a motion around Saturn on the equatorial plane.

These dust particles with a mass m get an electrostatic charge Q_0 once they are in the magnetospheric medium in accordance with the current balance among the electron collection current, the ion collection current, the current due to secondary electrons and the photoelectron emission current. These currents depend on the material parameters, on the properties of the magnetospheric plasma, on the relative speed of the dust particles to the plasma, and on the electrostatic potential of the dust particles (Horányi 1996).

The behavior of dust particles injected in the magnetospheric medium from the Aegaeonian surface is strongly modulated by the electromagnetic and gravitational forces; on the other hand, it is weakly modulated by other effects, like drag plasma and radiation pressure (Hill & Mendis 1979). In the Kronian system, Aegaeon is located at 2.77 $R_{\rm S}$ (1 $R_{\rm S} = 6.0324 \times 10^4$ km) from the center of the planet and its orbit around Saturn has an inclination of $0.0010° \pm 0009°$, and an eccentricity of 0.00024 ± 0.00023 (Hedman et al. 2010).

Dust particles ejected from the satellite surface are immediately charged in the magnetospheric medium. The planet is considered to be a spherical body with a magnetic field produced by a centered dipole. Under that assumptions (Figure 1), the equation of motion of a dust grain in the planetocentric inertial frame is:

$$m\ddot{\mathbf{r}} = \frac{Q_0}{c}\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) - \frac{GMm}{r^3}\mathbf{r}, \tag{1}$$

where M is the planetary mass, $\mathbf{B} = -B_0(R/r)^3\hat{z}$ is the magnetic field of Saturn, R is the planetary radius; m, Q_0 and $\mathbf{v}$ are mass, electrostatic charge and the velocity of the dust particles respectively, G is the gravitational constant and $\mathbf{E}$ is the co-rotational electric field given by:

$$\mathbf{E} = -\frac{(\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B}}{c}, \tag{2}$$

with $\mathbf{\Omega} = \Omega\hat{z}$ the planetary angular velocity, and c the speed of light.

In equation (1), the electrostatic charge (Q_0) is related to the grain surface potential ϕ which depends not only on the physical properties of the particle, but also on the local plasma properties of the Saturnian magnetosphere. The surface potential and its possible variations, are expected to be in the range $-5\,V < \phi < +5\,V$ (Horányi 2000;

Horányi et al. 2009). In the inner magnetosphere of Saturn (<7 R_S) there are two regions where the grain surface potential is expected to be positive (Kempf et al. 2005); therefore, in this work it is assumed that grains of all sizes ejected from Aegaeon's surface are instantaneously charged up to an equilibrium surface potential, which remains constant throughout their motion and reaches the maximum magnitude; $+5\,V$, once they are in the magnetospheric medium.

From equations (1) and (2), the equation of motion is written as:

$$\ddot{\mathbf{r}} = \frac{Q_0}{mc}\big[-(\mathbf{\Omega}\times\mathbf{r})+\mathbf{v}\big]\times\mathbf{B} - \frac{GM}{r^3}\mathbf{r}, \tag{3}$$

which can be rewritten in a cylindrical coordinate system ($\hat{r}$,$\hat{\theta}$,$\hat{z}$) considering that:

$$\mathbf{r} = r\hat{r}, \qquad \mathbf{v} = \dot{\mathbf{r}} = \dot{r}\hat{r} + r\dot{\theta}\hat{\theta},$$
$$\ddot{\mathbf{r}} = (\ddot{r} - r\dot{\theta}^2)\hat{r} + \frac{1}{r}\frac{d}{dt}(r^2\dot{\theta})\hat{\theta}. \tag{4}$$

Therefore, the equation of motion is:

$$(\ddot{r} - r\dot{\theta}^2)\hat{r} + \frac{1}{r}\frac{d}{dt}(r^2\dot{\theta})\hat{\theta} = -\frac{Q_0B_0R^3}{mcr^2}\left[(\dot{\theta}-\Omega)\hat{r} - \frac{\dot{r}}{r}\hat{\theta}\right] - \frac{GM}{r^2}\hat{r}, \tag{5}$$

for which the radial and angular components are the following:

$$\ddot{r} - r\dot{\theta}^2 = \frac{A(\dot{\theta}-\Omega) - GM}{r^2}, \tag{6}$$

$$\frac{d}{dt}(r^2\dot{\theta}) = -\frac{A\dot{r}}{r^2}, \tag{7}$$

where, for simplicity, a parameter $A = -Q_0B_0R^3/mc$ has been defined.

If the dust source (Aegaeon in this case) is located at a distance r_0 from the center of Saturn, we integrate equation (7) from r_0 to r in order to obtain the speed of the dust grain:

$$\dot{\theta} = \frac{A}{r^3} + \frac{1}{r^2}\left(r_0\,v_{0\theta} - \frac{A}{r_0}\right), \tag{8}$$

where $v_{0\theta} = r_0\dot{\theta}_0$ is the initial angular speed of the dust grain.

Additionally, the radial component (equation 6) can be rewritten as:

$$v_r\frac{dv_r}{dr} = r\dot{\theta}^2 + \frac{A\dot{\theta}}{r^2} - \frac{(A\Omega + GM)}{r^2}, \tag{9}$$

considering that $v_r = dr/dt = \dot{r}$, and $\ddot{r} = v_r dv_r/dr$.

Now, by replacing $\dot{\theta}$ from equation (8) in the equation (9) we have:

$$v_r\frac{dv_r}{dr} = \frac{2A^2}{r^5} + \frac{3A}{r^4}\left(r_0\,v_{0\theta} - \frac{A}{r_0}\right) + \frac{1}{r^3}\left(r_0\,v_{0\theta} - \frac{A}{r_0}\right)^2 - \frac{(A\Omega+GM)}{r^2}. \tag{10}$$

Integrating from r_0 to r and setting the parameter $x = r/r_0$, equation (10) is written as follows:

$$v_r{}^2 - v_{0r}{}^2 = -\frac{A^2}{r_0^4}\frac{(1-x)^2}{x^4} - \frac{2Av_{0\theta}}{r_0^2}\frac{(1-x)}{x^3} - v_{0\theta}{}^2\frac{(1-x^2)}{x^2} + 2\frac{(A\Omega+GM)}{r_0}\frac{(1-x)}{x}, \tag{11}$$

where $v_{0r} = v_r(r_0)$ is the initial radial speed of the dust grain.

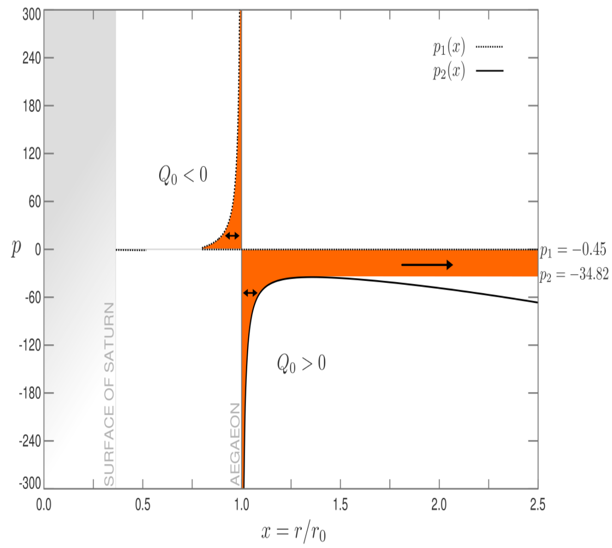

Fig. 2. The confinement (capture) and escape regimes for negatively ($Q_0 < 0$) and positively ($Q_0 > 0$) charged dust particles. The shaded regions (orange color) in the plane p-x correspond to regimes where real orbits can exist, and the arrows indicate the dust grain movement direction. It is shown where the Saturn's surface and the ejection point (Aegaeon) are located.

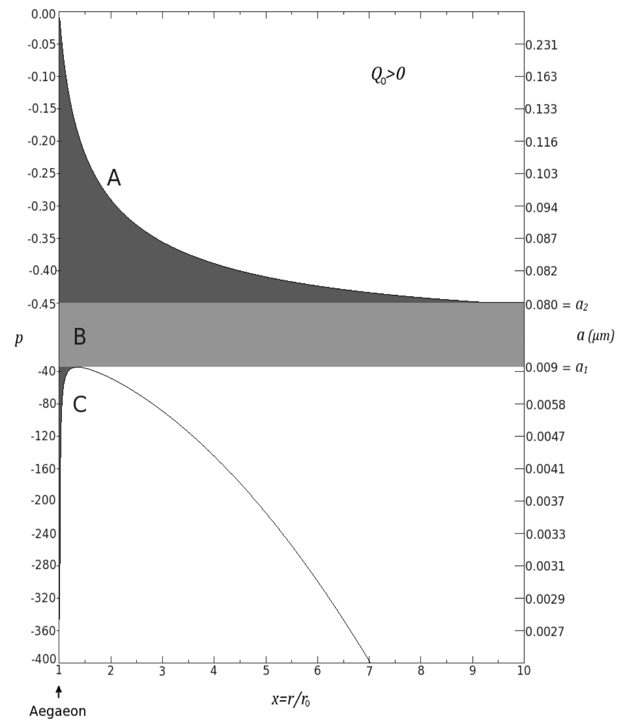

Fig. 3. The confinement and capture regimes for positively charged particles ($Q_0 > 0$ and $p < 0$) ejected from Aegaeon surface. **A** and **C** represent, the dust confinement regimes and **B** contains escaping dust grains.

2.1. *Dust particles initial speed*

Assuming that the dust particles are ejected at an initial distance r_0, which corresponds to the distance from the dust source (Aegaeon) to the center of Saturn, the magnitude of the initial speed of the dust particles (v_0) can be defined from the magnitude of the orbital speed of Aegaeon ($v_{\rm orb}$) and the magnitude of the dust escape speed from this satellite (v_e).

The orbital speed of Aegaeon around Saturn at a distance r_0, is given by:

$$v_{\rm orb} = \sqrt{\frac{KGM}{r_0}}, \tag{12}$$

where K=1 corresponds to the Keplerian velocity and M represents the planetary mass. On the other hand, the grain escape speed v_e from Aegaeon is given by:

$$v_e = \sqrt{\frac{2GM_A}{R_A}}, \tag{13}$$

with M_A and R_A the mass and the radius of Aegaeon, respectively.

Using the data for Saturn and Aegaeon[1], $v_{\rm orb}$ and v_e are calculated considering that Aegaeon follows a Keplerian orbit. These velocities differ by four orders of magnitude, and so dust particles have enough energy to escape from the Aegaeonian gravitational field. Since Aegaeon's orbit speed (54,270 km/h) is much larger than the escape speed from Aegaeon (1 km/h), we assumed that the dust grains are launched in the forward direction with the Kepler speed of Aegaeon (i.e. K=1).

As a consequence of this fact, dust particles move in the planetary equatorial plane (r,θ) around Saturn (equation 12), where the components of the initial speed are given by:

[1]Central Bureau for Astronomical Telegrams, IAU, Circular No. 9023.

$$v_{0r} = 0, \qquad \text{and} \qquad v_{0\theta} = \sqrt{\frac{GM}{r_0}}. \tag{14}$$

Replacing the grain speed (equation 14) in equation (11), the radial speed component is:

$$v_r{}^2 = -\frac{A^2}{r_0^4}\frac{(1-x)^2}{x^4} - \frac{2A}{r_0^2}\sqrt{\frac{GM}{r_0}}\frac{(1-x)}{x^3} - \frac{GM}{r_0}\frac{(1-x^2)}{x^2} + \frac{2(A\Omega+GM)}{r_0}\frac{(1-x)}{x}. \tag{15}$$

If $p = A\Omega/GM$, $L_0 = r_0/R$ and $\alpha = GM/\Omega^2 R^3$, equation (15) becomes:

$$\left(\frac{r_0}{GM}\right) v_r^2 = -\frac{(1-x)^2}{x^2} + \left[\frac{2(1-x)}{x^3}\left(x^2 - \frac{\alpha}{L_0^{3/2}}\right)\right] p - \left[\frac{\alpha^2(1-x)^2}{L_0^3 x^4}\right] p^2, \tag{16}$$

where p is a dimensionless parameter and represents the ratio between the electromagnetic force and the gravitational force; meanwhile, L_0 is called the McIlwain parameter (or the magnetic parameter) that indicates the source ejection distance from the center of the planet (McIlwain 1966).

Since v_r^2 is a positive definite quantity, the radial expression from equation (16) is:

$$p^2 - \frac{2L_0^3}{\alpha^2}\frac{x}{1-x}\left(x^2 - \frac{\alpha}{L_0^{3/2}}\right) p + \frac{L_0^3 x^2}{\alpha^2} \leq 0. \tag{17}$$

Equation (17) is a quadratic in p and it can be expressed as $F = F(p, x)$ with the solutions $p_1(x)$ and $p_2(x)$.

According to our model, the radial velocity of the particle will be zero if $x = 1$. Thus, no particles can cross Aegaeon's orbit and $x = 1$ forms another bound on the radial motion of any particle.

In this analysis we supposed that Aegaeonian dust grains are spherical ($m = 4/3\pi a^3\rho$), and, under the assumption that Saturnian rings are mainly composed of water-group molecules (Cuzzi et al. 2009; Hedman et al. 2013; Filacchione et al. 2013), we considered that dust grains are made of water ice ($\rho = 1\,\mathrm{g/cm^3}$). The dust grains may also be considered as a collection of isolated particles where the electrostatic charge is related to the grain surface potential as $Q_0 = a\phi$ (Mendis & Rosenberg 1994). As a result, the dimensionless parameter p and the dust grain radius a (in μm) are related, i.e. $p = A\Omega/GM$ ($p = -Q_0 B_0 R^3 \Omega/MGmc$).

Equation (17) has two solutions associated with escape and confinement (capture) regimes in the Aegaeon environment (Figure 2). Our model can accomodate particles with positive or negative charge ($\phi = \pm 5$ volts) in the Saturnian magnetospheric medium. Negatively charged dust particles ($x < 1$, $p > 0$) subject to gravity and electromagnetic forces will move radially inwards; meanwhile, positively charged grains ($x > 1$, $p < 0$) will move radially outwards. Negatively charged grains could be confined between Aegaeon's orbit and the synchronous orbital distance, while positively charged grains could be remain near to Aegaeon or escape to the magnetospheric medium. As Aegaeon is located in the inner boundary of the G-ring, in this work we focus our analysis on the positively charged dust particles because they could be associated to a ring-like structure and could be involved in an escape regime. As a result, for positively charged particles ($Q_0 > 0$) it is posible to identify three different regimes (**A**, **B** and **C**, see Figure 3) for which the radius size of dust particles is calculated using Saturnian planetary parameters: $M = 5.668 \times 10^{29}$ g, $R = 6.0268 \times 10^9$ cm, $\Omega = 1.691 \times 10^{-4}$ rad/s, and $B_0 = 0.21$ gauss. Finally, for positive dust particles ($\phi = +5\,V$) the grain radius a (in μm) in terms of the dimensionless parameter p is calculated by the mathematical expression:

$$a = \frac{0.0516}{\sqrt{|\,p\,|}}. \tag{18}$$

3. RESULTS AND DISCUSSION

Figures 2 and 3 show the solutions for equation (17) where three different regimes are well identified. In Figure 3, **A** and **C** represent the confinement regimes; meanwhile, **B** represents the regime where dust particles can escape.

Regime **A** contains dust particles with size $a > a_2$ ($a_2 = 0.08$ μm), regime **B** is created by dust particles in the interval $a_2 \geq a \geq a_1$ which corresponds to $p_2(x) \leq p \leq p_1(x)$, and regime **C** includes dust particles with size $a < a_1$ ($a_1 = 0.009$ μm).

TABLE 1

CONFINEMENT (**A** AND **C**) AND ESCAPE (**B**) REGIMES OF THE AEGAEONIAN POSITIVE DUST PARTICLES RELATED TO THE G-RING

Regime	Parameter p	Grain radius $a(\mu\text{m})$	Escape regime Velocity $v(\text{km s}^{-1})$	Escape regime Time $t(\times 10^5$ s)
A	> -0.45	> 0.08		
B	$-0.45 \leq p \leq -34.82$	$0.08 \geq a \geq 0.009$	$22.12 \leq v \leq 194$	$1.41 \geq t \geq 0.16$
C	< -34.82	< 0.009		

The motion of dust particles in regime **A** can be described by the theory of adiabatic charged particle motion (Northrop 1963). For those grains near the escape regime, the motion is partially modulated by the electromagnetic force; meanwhile, the larger grains in this regime are gravitationally dominated. All dust particles within regime **A** are distributed around Saturn as part of a tenuous ring-like structure that is radially extended from Aeageon to the vicinity of E-ring.

Regime **B** corresponds to the region where the gravitational and electromagnetic forces have comparable influence on the particle orbit; therefore, the dust particles dynamics is strongly influenced by the Lorentz force, which is responsible for these grains' escape from the Aegaeon vicinity. These grains travel across the magnetospheric medium with velocities of the order of km s^{-1} and they can interact with the energetic populations (ions and electrons) of the Saturnian magnetospheric plasma.

All dust particles in regime **C** move in non-periodic electrodynamic orbits that will be smaller as p becomes very large (in absolute value); then the particle excursions become smaller and the motion of the grains approximates to an elliptical gyration over a guiding center (the adiabatic approximation), which drifts around the planet with a speed close to the Saturnian co-rotational speed.

3.1. *Confinement regions of Aegaeonian dust particles*

From Figure 3, regimes **A** and **C** represent not only the locations where dust particles remain close to Aegaeon (point of injection), but also the places where they could be feeding the magnetospheric space to form a ring-like structure. Particles with a radius greater than 0.08 microns remain in regime **A**. These results are in good agreement with the dust grains sizes detected by the Cassini instruments (1.0 μm to 10 μm, and even larger) that were reported by Hedman et al. 2007.

Because dust grains in regime **C** are very small and can have sizes of the order of several molecules ($\approx$ tenths of nm), their motion is held up by the magnetic force and they can drift around Saturn with the co-rotational speed.

An adiabatic approximation analysis for these dust particles ($a < 0.009$ μm and $a > 0.08$ μm) shows that the Larmor radius ($r_L = mvc/Q_0B_0$) is $r_L < 4.13 \times 10^2$ km for small particles ($a < 0.009$ μm) in regime **C**, and it is $r_L > 3.20 \times 10^4$ km for particles $a > 0.08$ μm in regime **A** (Table 1).

From the last results, grains in regime **A** reach a radial extent beyond 1×10^4 km, which means that, G-ring is located inside the region described by the Larmor radius of these dust particles.

For grains in regime **C** the Larmor radius is smaller than the G-ring radial extent, indicating that all these dust particles are almost attached to Aegaeon orbit, forming part of the G-ring.

3.2. *Dusty Regions*

Although regimes **A** and **C** are associated with confinement of particles and regime **B** is related to escaping grains, dusty material produced by impacts on Aegaeon is distributed around Saturn building the G-ring, and/or it is sent to external magnetospheric regions.

It is also inferred from the results that dust particles in regime **A** could be part of G-ring and could be also immersed in the Saturnian E ring (3–8 R_S) because of the size of the Larmor radius. Particles that reach the inner E-ring could contribute to the sub-micron particle population there.

Dusty material in regime **C** could be the smallest dust population of the G-ring close to the Aegeonian satellite forming part of its bright arc or/and perhaps it could contribute to create very small moonlets by an electrostatic coagulation process.

Dust grains in regime **B** (Figure 3) could be ejected from the Saturnian magnetosphere if they are in the interval $-0.45 \leq p \leq -34.82$ that corresponds to $0.08\ \mu\text{m} \geq a \geq 0.009\ \mu\text{m}$. These positively charged grains could travel and reach regions far from the Saturnian inner magnetosphere, because they are ejected with velocities in the range $13.4\ \text{km s}^{-1} \leq v \leq 119.4\ \text{km s}^{-1}$, which correspond to the escape time from the magnetospheric medium in the interval $2.23 \times 10^5\ \text{s} \geq t \geq 0.25 \times 10^5\ \text{s}$ (Table 1). Because of this, dust material in regime **B** could escape from the neighborhood of Aegaeon and travel across the Saturnian magnetosphere.

According to Waite et al. (2006) the dust production rate by Enceladus is 93 kg s^{-1}. Meanwhile, Giuliatti-Winter et al. (2013) report that the dust production rate in the surface of Aegaeon is 5.9×10^{-6} kg s^{-1}. Comparing both results, the Aegaeonian dust particles are not a considerable contribution to the E-ring. Consequently, it would be very difficult to identify which particles come from the G-ring.

4. CONCLUSIONS

Aegaeon provides sub-micron and nanometric dusty material to the G-ring. These dust populations remain near to Aegaeon's orbit (2.77 R_S). The dusty material emanating from the Aegaeonian surface is part of the G-ring and could be a very small population of the E-ring where it could not be detected, in contrast with the E-ring dust populations.

This work was supported by DGAPA-UNAM grant IN107612.

REFERENCES

Axford, W. I., & Mendis, D. A. 1974, Ann. Rev. Ear. Plan. Sci., 2, 419

Cuzzi, J., Clark, R., et al. 2009, Saturn from Cassini-Huygens, Ring Particle Composition and Size Distribution, ed. M. K. Dougherty, L. W. Esposito, & S. M. Krimigis (Berlin: Springer), 459

Filacchione, G., et al. 2013, ApJ, 766, 76

Giuliatti-Winter, S. M., Sfair, R. R., & Mourão, D. D. 2013, AAS-DDA Meeting, 44, 204.08

Hamilton, D. P. 1993, Icarus, 101, 244

Hedman, M. M., Burns, J. A., Tiscareno, M. S., & Porco, C. C. 2009a, Icarus, 202, 260

Hedman, M. M., Cooper, N. J., Murray, C. D., Beurle, K., Evans, M. W., Tiascareno, M. S., & Burns, J. A. 2010, Icarus, 207, 433

Hedman, M. M., Murray, C. D., Cooper, N. J., Tiascareno, M. S., Beurle, K., Evans, M. W., & Burns, J. A. 2009b, Icarus, 199, 378

Hedman, M. M., Nicholson, P. D., Cuzzi, J. N., Clark, R. N., Filacchione, G., Capaccioni, F., & Ciarniello, M. 2013, Icarus, 223, 105

Hedman, M. M., et al. 2007, Science, 317, 653

Hill, J. R., & Mendis, D. A. 1979, M&P, 21, 3

Horányi, M. 1996, Proceedings of the Sixth Workshop, The Physics of Dust Plasmas, ed. P. K. Shukla, D. A. Mendis, & V. W. Chow, (La Jolla, CA), 33

Horányi, M. 2000, Phys. of Plasmas, 7, 3847

Horányi, M., Burns, J. A., Hedman, M. M., Jones, G. H., & Kempf, S. 2009, in Saturn from Cassini-Huygens, ed. M. K. Dougherty, L. W. Esposito, & S. M. Krimigis (New York, Springer), 511

Hsu, H.-W., Krüger, H., & Postberg, F. 2012, Astrophysics and Space Science Library, ed. I. Mann, N. Meyer-Vernet, & A. Czechowski, (Springer-Verlag, Berlin), 385, 77

Jontof-Hutter, D., & Hamilton, D. P. 2012, Icarus, 218, 420

Kempf, S., Srama, R., Horányi, M., Burton, M., Helfert, S., Moragas-Klostermeyer, G., Roy, M., & Grün, E. 2005, Nature, 433, 289

Maravilla, D., Flammer, K. R., & Mendis, D. A. 1995a, ApJ, 438, 968

_________. 1995b, Ap&SS, 234, 233

_________. 1996, Proceedings of the Sixth Workshop, The Physics of Dust Plasmas, ed. Shukla, P. K., Mendis, D. A., & Chow, V. W. (La Jolla, CA), 47

Maravilla, D., & Flandes, A. 2005, Geophys. Res. Lett., 32, 6202

McIlwain, C. E. 1966, Space Sci. Rev., 5, 585

Mendis, D. A., Hill, J. R., & Houpis, H. L. F. 1983, J. Geophys. Res., 88, 929

Mendis, D. A., Houpis, H. L. F., & Hill, J. R. 1982, J. Geophys. Res., 87, 3449

Mendis, D. A., & Rosenberg, M. 1994, ARA&A, 32, 419

Mitchell, C. J., HoráNyi, M., & Howard, J. E. 2003, J. Geophys. Res.(Space Physics), 108, 1179

Northrop, T. G. 1963, Review of Geophysics and Space Physics, 1, 283

Northrop, T. G., & Hill, J. R. 1982, J. Geophys. Res., 87, 6045

Porco, C. C., Thomas, P. C., Weiss, J. W., & Richardson, D. C. 2007, Science, 318, 1602

Schaffer, L., & Burns, J. A. 1994, J. Geophys. Res., 99, 17211

Throop, H. B., & Esposito, L. W. 1998, Icarus, 131, 152

Waite, J. H. et al. 2006, Science, 311, 1419

J. L. Leal-Herrera and Dolores Maravilla: Departamento de Ciencias Espaciales, Instituto de Geofísica, Universidad Nacional Autónoma de México, Circuito de la investigación Científica s/n, Ciudad Universitaria, Delegación Coyoacán, C.P. 04150, México D.F., Mexico (joseluis.leal@gmail.com, dmaravil@geofisica.unam.mx).