Small particles in Pluto’s environment: effects of the solar radiation pressure

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Accepted 2013 January 11. Received 2012 December 22; in original form 2011 November 25

ABSTRACT
Impacts of micrometeoroids on the surfaces of the plutonian small satellites Nix and Hydra can generate dust particles. Even in this region so far from the Sun these tiny ejected particles are under the effects of the solar radiation pressure.

In this work, we investigate the orbital evolution of the escaping ejecta from both the small satellites under the effects of the radiation pressure combined with the gravitational effects of Pluto, Charon, Nix and Hydra. The mass production rate of micron-sized dust particles generated by micrometeoroids hitting the satellites is obtained, and numerical simulations are performed to derive the lifetime of the ejecta. These pieces of information allow us to estimate the optical depth of a putative ring, which extends from the orbits of Nix to Hydra.

The ejected particles, between the orbits of Nix and Hydra, form a wide ring of about 16 000 km. Collisions with the massive bodies and escape from the system are mainly determined by the effects of the solar radiation pressure. This is an important loss mechanism, removing 30 per cent of the initial set of 1 μm-sized particles in 1 yr. The surviving particles form a ring too faint to be detectable with the derived maximum optical depth of $4 \times 10^{-11}$.

Key words: Kuiper belt objects; individual: Pluto – planets and satellites: rings.

1 INTRODUCTION
Since the discovery of Nix and Hydra by Weaver et al. (2006) much effort has been made in order to find new satellites and rings in the Pluto system. As proposed by many authors these rings would be essentially composed of material produced from collisions between Pluto’s satellites and small Kuiper belt (KB) debris (Thiessenhusen et al. 2002; Stern et al. 2006; Steffl & Stern 2007). Such kind of impact is also expected to be the source of dynamical transport of grains between bodies in the Pluto system, and should be responsible for the photometric evolution of Pluto’s satellites reaching similar colours and albedos (Stern 2009). However, similar albedos would imply high-density values for Nix and Hydra in disagreement with their current values of masses as Canup (2011) pointed out.

Thiessenhusen et al. (2002) have showed that a dust cloud, mainly formed by ejecta produced by impacts of micrometeoroids on the surface of Charon, can exist around the Pluto–Charon binary. In their model, the orbits of the ring particles were disturbed only by the gravitational effects of the two massive bodies, and the effects of the solar radiation pressure were neglected. The resulting dust cloud would be very tenuous with a maximum optical depth of $3 \times 10^{-11}$.

After the discovery of Nix and Hydra, a crude estimate of the optical depth of rings in the region between these satellites was presented by Stern et al. (2006). Assuming a mean lifetime to the pure ice particles released from Nix and Hydra to be $10^5$ yr, and taking no perturbing forces into account, a much higher optical depth of $5 \times 10^{-6}$ was derived.

A particle escapes from a parent body when the initial speed is larger than the satellite’s escape velocity ($v_{esc}$). Large bodies like Pluto and Charon will probably provide less impact ejecta than small moons like Nix and Hydra will. In the case of Pluto and Charon, the ejecta generated from such collisions is expected to re-impact on to their surfaces on the basis of their high escape velocities, about 1.2 and 0.6 km s$^{-1}$, respectively, as it was discussed in Stern et al. (2006) and Steffl & Stern (2007). On the other hand, Nix and Hydra present significantly small escape velocities, at least one-order-of-magnitude smaller than the escape velocity of Charon.

The first observational constraint on Pluto’s rings is present in Steffl & Stern (2007). Based on the data acquired by the Hubble Space Telescope, they showed that the upper limit of optical depth for rings in the Pluto system is $1.3 \times 10^{-5}$. Given their optical depth constraint, they also estimated a lifetime of 900 yr for particles of such a ring spanning the region between the orbits of the small satellites.

In the work of Poppe & Horányi (2011) they extended the model of Thiessenhusen et al. (2002) by including the ejecta from the surfaces of Nix and Hydra and effects of the solar radiation pressure.
Dust grains with radii from 0.1 to 100 μm were launched from Pluto and its moons with velocity between 0.7 and 2.0 times the \( v_{esc} \) of each parent body. As a result, Nix and Hydra increase the optical depth of a putative ring in the Pluto system up to four orders of magnitude of the previous value (\( \sim 10^{-11} \)) obtained by Thiessenhusen et al.

Here, we analyse the contribution of the small satellites Nix and Hydra to form, via a mechanism of ejecta production, a tenuous ring in the Pluto system, as it has been shown by Thiessenhusen et al. (2002) in this region (about 45–58 plutonian radii) almost no ejecta comes from the collisions on the surfaces of Pluto and Charon (see their fig. 4).

This paper is divided in four sections. In Section 2, we analyse the parameter \( C \) which is the ratio between the solar radiation pressure and the gravity of Pluto (Hamilton & Krivov 1996). This parameter allows us to verify the importance of the solar radiation pressure in Pluto’s environment. Afterwards, we numerically simulate a sample of ejected particles from the surfaces of Nix and Hydra under the effects of the radiation pressure and the gravity of the four massive bodies. In our model, Pluto follows an eccentric orbit and its tilted rotational axis was included. In Section 3, we estimate the mass production rates of dust released from the moons through an analytical model. The combined results, analytical and numerical, can help us to constraint an optical depth of a putative ring system. Our conclusions are presented in the last section.

2 FORCES ACTING ON THE DUST PARTICLES

In the following subsections, we analyse the evolution of launched dust particles from the surfaces of Nix and Hydra under the gravitational effects of the four massive bodies and the solar radiation pressure.

2.1 The strength of the perturbing force

Given current observational limit and the impact mechanism, which is credited to produce a hypothetical ring around Pluto, if a tenuous ring exists within the system it would be composed mainly of micrometric particles, for which the effect of the solar radiation may be significant.

The solar radiation force can be split into two components: the Poynting–Robertson drag (PR drag hereafter) and the radiation pressure (RP component hereafter). Each component acts in different time-scales and has a distinctive effect on the orbit of the particle: the PR drag is a slow acting force and it is mainly responsible for the collapse of the particle’s orbit in a time-scale \( > 10^5 \) yr; on the other hand, the RP component can change the eccentricity of the particle in a time-scale comparable to the orbital period of the planet (\( \sim 10^5 \) yr in this case). Since our analysis is limited to \( 10^5 \) yr, the former component has no significant effect. An extensive study of the effects of both components can be found in Burns et al. (1979).

In order to verify if the RP component has a significant influence on the orbital dynamics of micrometric particles in the Pluto system, we calculated the dimensionless parameter \( C \). This parameter gives the relative strength between the solar radiation force and the planetary gravity, as defined by Hamilton & Krivov (1996). In a simplified form it can be written as

\[
C = \frac{9}{8} \frac{n_i}{n_s} \frac{Q_{pr}}{G M C P S} r^2 v_s \cos \theta,
\]

where \( n \) is the particle’s mean motion about the planet and \( n_i \) is the mean motion of the planet around the Sun, \( r \) is the position vector of the particle and \( r = |r| \), \( F_s \) is the solar radiation flux density at the heliocentric distance of Pluto, \( Q_{pr} \) is the radiation pressure efficiency factor, \( c \) is the speed of light, \( G \) is the gravitational constant, \( M \) is the mass of Pluto, and \( \rho \) and \( s \) are the density and the radius of the grain, respectively. The orbital elements and physical parameters of Pluto are listed in Table 1.

The variation of \( C \) as a function of the distance from Pluto can be seen in Fig. 1 for two particles of 1 and 10 μm in radius. The grains are adopted to be spherical with a uniform density equals to 1 g cm\(^{-3}\) and \( Q_{pr} \) was assumed to be 1 (Burns et al. 1979).

As expected, small particles are more sensitive to the effects of the solar radiation pressure than large particles. The strength of \( C \) is \( \sim 10 \) for a 1 μm-sized particle and \( \sim 1 \) for a 10 μm-sized particle placed between the orbits of Nix and Hydra, about 45–58 plutonian radii (the grey area shown in Fig. 1).

We compared the results presented in Fig. 1 with a previous analysis by Sfair & Giuliani Winter (2009) on the orbital evolution of small particles located at the \( \mu \) and \( \nu \) rings of Uranus. Their results showed that \( C \) is \( \sim 1 \) for a 1 μm-sized particle (see their fig. 2), smaller than the value shown in our Fig. 1. Their numerical simulations did confirm that the solar radiation pressure has an important effect on the orbital evolution of dust particles located in the \( \mu \) and \( \nu \) rings. Although Pluto is further from Sun, its small size, relative to the giant planets, makes the solar radiation pressure an important force to be taken into account in the analysis of the orbital evolution of dust particles (Pires dos Santos, Giuliani Winter & Sfair 2010).

![Figure 1. Parameter C as a function of the distance from Pluto for a spherical grain with 1 (dotted line) and 10 μm (dashed line) in radius and density equals to 1 g cm\(^{-3}\). The grey area represents the radial distance between the orbits of Nix and Hydra.](https://academic.oup.com/mnras/article-abstract/430/4/2761/1098428)
2.2 Numerical simulations

In order to investigate the orbital evolution of grains ejected from Nix and Hydra, we numerically simulated a sample of particles under the combined effects of the gravity field of the four massive bodies and the RP component. In an inertial reference frame, the solar radiation force can be written as

$$m_p \ddot{v} = \frac{F_{\text{RAD}}}{c} S,$$

where $m_p$ is the particle’s mass moving with velocity $v$, $A$ is the cross-section of the particle and $S$ is a unit vector in the direction of the incident radiation (Burns et al. 1979).

The initial conditions of Charon, Nix and Hydra are listed in Table 2. The large eccentricity of Pluto makes it necessary to take into account the variation of the solar flux during its orbit around the Sun. Secondary effects like the planetary shadow and the light reflected from the planet were neglected, since both effects are weaker than those caused by the RP component (Hamilton & Krivov 1996). The Yarkovsky effect was also neglected since it is irrelevant for particles in the micrometre-sized range.

The typical size distribution of dust rings follows a power law (Burns, Hamilton & Showalter 2001, equation 3); here we adopted index $q = 3.5$. It shows that the population is dominated by small grains; thus, in our numerical simulations we assumed particles from 1 to 10 $\mu$m in radius as a representative set of this distribution. For each size (1, 5, 10), we simulated 360 particles for the time span of $10^3$ yr. The integrations were performed by using the Bulirsch–Stöer algorithm from Mercury 6 package (Chambers 1999) including the force described in equation (2). The motion of a particle is integrated until it exceeded a distance of 100$a_0$ ($\sim 2 \times 10^6$ km) from Pluto or when it hits one of the massive bodies. The number of collisions and ejections were recorded. We do not include the dust production rate from Pluto and Charon, since aforementioned works have shown that the typical velocity of particles generated by collisions between small KB debris and objects of the Pluto system is much lower than the required escape velocity for them leaving the surfaces of Pluto or Charon.

According to Krüger, Krivov & Grün (2000), impact experiments suggest that the initial speed distribution of ejecta follows a power law, which depends on the surface of the target and a lower cutoff velocity. Our calculations showed that for Nix and Hydra the minimum ejection velocities happen to be close to the escape velocity of the satellites, and present a steep decay. Therefore, we restricted ourselves to analyse $v = v_{\text{esc}}$. Another simplification was made regarding the angular distribution of the ejecta, which was assumed to have the velocity vector always normal to the surface of the satellites.

Table 2. Orbital and physical parameters derived by Tholen et al. (2008). The parameters of the Charon’s orbit are relative to Pluto, and the parameters of the orbits of Nix and Hydra are relative to the centre of mass of the Pluto–Charon system. The masses of Nix and Hydra were obtained by assuming that the density equals to 1.63 g cm$^{-3}$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Charon</th>
<th>Nix</th>
<th>Hydra</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$ (km)</td>
<td>19 570.3 ($a_0$)</td>
<td>49 240.0</td>
<td>65 210.0</td>
</tr>
<tr>
<td>$e$</td>
<td>0.0035</td>
<td>0.0119</td>
<td>0.0078</td>
</tr>
<tr>
<td>$i$ (deg)</td>
<td>96.168</td>
<td>96.190</td>
<td>96.362</td>
</tr>
<tr>
<td>Diameter (km)</td>
<td>1212</td>
<td>88</td>
<td>72</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$1.52 \times 10^{21}$</td>
<td>$5.8 \times 10^{17}$</td>
<td>$3.2 \times 10^{17}$</td>
</tr>
<tr>
<td>$P$ (d)</td>
<td>6.38</td>
<td>25.49</td>
<td>38.85</td>
</tr>
</tbody>
</table>

The oblateness of the central body can decrease the maximum eccentricities reached by the dust particles due to the RP component (Horányi, Burns & Hamilton 1992). So far the oblate gravity coefficient ($J_2$) of Pluto is unknown, nevertheless by adopting Beauvalet et al. (2012) estimate, then we investigate if the oblateness displays an important role on the orbital evolution of the particles. We verified the effects of including Pluto’s $J_2$ (estimate of $O(10^{-4})$) in two ways: through the oblateness parameter by Hamilton & Krivov (1996, equation 4) and numerical simulations with and without it for the same set of grains described previously. The effects of the oblateness, following the quoted equation (4), are at least $10^3$ weaker than the radiation pressure for particles launched at the location of Nix and/or Hydra. The numerical simulations corroborate this result: the particles essentially have the same fate with or without the inclusion of Pluto’s $J_2$. Therefore, the radiation pressure is a strong perturbation farther from Pluto, and the planetary oblateness can be safely neglected. Hereafter we only consider the sample of simulations without the oblateness.

We now discuss the outcomes of the dust ejection. The sample of 1 $\mu$m-sized particles was completely scattered in a very short time-scale. In less than 1 yr, considerable quantity of these tiny particles cross the orbit of Charon and can collide with one of the members of the binary (Fig. 2). Those particles which remain longer in the system are mostly removed by ejection. Nevertheless, at this time they are already very far from the satellites or they are in hyperbolic orbits; for a couple of years large particles (5 and 10 $\mu$m) are distributed in a region encompassing the orbits of Nix and Hydra (Fig. 3), without significant loss of material.

The amount of particles as a function of time can be seen in Figs 4(a) for 1 and (b) for 10 $\mu$m-sized particles. As expected large particles remained in the system much longer than the small particles, regardless of the source. In 5 years, 98 per cent of the 1 $\mu$m-sized grains were lost while it requires about 200 years to remove 90 per cent of the initial set of 10 $\mu$m-sized particles. Details on the lifetime of the escaping ejecta spanning the region between Nix and Hydra will be discussed in the next section.

A summary of collision and escape percentages is present in Table 3. The lifetimes of the grains launched from Nix and Hydra are mainly determined by collisions with Pluto and by ejections from the system. The large number of collisions with Pluto disagrees in part with the results of Stern (2009). He claims that Pluto’s surface is not affected by the particles ejected from the small satellites due to the gravitational perturbations of Charon and also by Pluto’s own annual atmospheric frost deposition cycle. Regarding specifically the dynamical evolution of the escaping grains, their motions are strongly affected by the radiation pressure, thus thanks to large changes in $e$, the particles often hit the central body. These effects were not considered in the aforementioned paper.

The loss of ejecta due to escape from the system reaches 70 per cent of the initial set of the 1 $\mu$m-sized grains. The transfer of material between the moons depends on the particle size, for the 10 $\mu$m-sized particles; the rate of ejecta exchange between the moons is less than 1 per cent. Our numerical simulations also showed that the re-impact of ejecta on to their source bodies is a less important loss mechanism than escape from the system, in agreement with Poppe & Horányi (2011). It is worth noting that the ejecta re-impacting on Nix and Hydra do not have enough energy to be a mechanism of dust production.

In the next section we analyse the mass and the normal optical depth of a hypothetical ring generated by impacts of interplanetary dust particles (IDPs) on the surfaces of Nix and Hydra. The comparison of the numerical results and the mass production rate can
help us to place an upper limit to the normal optical depth of a ring generated by this mechanism.

3 THE RING GENERATION PROCESS

First, we calculate the mass production of the ejected dust particles by analysing the mass flux of impactors at Pluto’s region and the parameter known as ejecta yield (Y). This analytical model follows the approach summarized in Sfair & Giuliodi Winter (2012).

The distribution of IDPs was measured in situ at Jupiter and Saturn distances (Humes 1980; Grün 1993). The dust counter onboard the Pioneer 10 spacecraft measured a nearly constant spatial distribution from 3 to 18 au (Humes 1980), after this distance the dust flux has not been directly measured. To estimate the ejecta production from Nix and Hydra’s surfaces it is necessary to know the flux of interplanetary dust crossing Pluto’s system. This flux can be obtained through an extrapolation of the data obtained by previous missions in the inner part of the Solar system. Estimates have been used to characterize the dust fluxes at all the giant planets distances (e.g. Krivov et al. 2003) and nearly the perihelion of Pluto (e.g. Thiessenhusen et al. 2002; Porter, Desch & Cook 2010).

Thus, we assume that the mass flux of impactors \( F_{\infty}^{imp} \) at Pluto is similar to the mass flux at Neptune, i.e. \( 1.0 \times 10^{-16} \) kg m\(^{-2}\) s\(^{-1}\) (Porter et al. 2010), which corresponds to the IDP flux at 30 au, close to the perihelion distance of Pluto. The superscript \( \infty \) indicates that this value was measured far from the central body and has to be corrected by the gravitational focusing by Pluto.

The correction due to the gravitational focusing is performed on the values of the dust grains’ speed \( v_{imp}^{\infty} \) and spatial density \( n_{imp}^{\infty} \). Both values are increased as the dust grains enter the Hill sphere of the central body.

The velocities of the IDPs relative to Pluto and far from it \( v_{imp}^{\infty} \) are given by \( v_{imp}^{\infty} = \sqrt{\epsilon^2 + i^2 v_p^2} \) (Thiessenhusen et al. 2002; Porter et al. 2010), where \( \epsilon \) and \( i \), taken to be 0.3, represent the mean eccentricities and inclinations of the dust population, respectively, and \( v_p \) is Pluto’s orbital velocity (about 6 km s\(^{-1}\)). We derived \( (v_{imp}/v_{imp}^{\infty}) \) (Colombo, Lautman & Shapiro 1966) and \( (n_{imp}/n_{imp}^{\infty}) \) (Spahn et al. 2006) at the satellite’s distance from the planet. Our results have shown that the difference between the mass flux of impactors far and close to Pluto is of \( O(10^{-3}) \). Therefore, we adopted the mass flux of impactors at Pluto’s region to be the value without this correction.

### Table 3. Collision and escape rates of dust launched from Nix and Hydra for different grain sizes, where P = Pluto, C = Charon, N = Nix, H = Hydra and E = escape from the system.

| Grain Size (µm) | Nix | | | | | | Hydra | | | | |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                 | P   | C   | N   | H   | E   | P   | C   | N   | H   | E   | P   | C   | N   | H   |
| 1               | 14  | 17  | 2   | 0   | 67  | 14  | 17  | 2   | 0   | 67  | 14  | 17  | 2   | 0   |
| 5               | 39  | 6   | 2   | 0   | 53  | 39  | 6   | 2   | 0   | 53  | 39  | 6   | 2   | 0   |
| 10              | 49  | 3   | 7   | 0   | 41  | 49  | 3   | 7   | 0   | 41  | 49  | 3   | 7   | 0   |

### Figure 2. Snapshots, viewed from the top in the barycentric reference frame, of dust launched from Nix and Hydra indicated by black points for the grain radius of 1 µm. The positions of Charon, Nix and Hydra are indicated by lines, for one orbital period of each satellite. The time is shown on the top of each snapshot.
The mass production rate \( (M^+) \) from the surface of a moon via impact process is a function of the flux of impactors, the cross-section area of the moon and the ejecta yield. Through impact experiments in laboratory, Koschny & Grün (2001) derived an empirical relationship for \( Y \) which depends on the fraction of ice-silicate in the target, the impactor’s mass \( (m_{\text{imp}}) \) and \( v_{\text{imp}} \). Here, we assume that Nix and Hydra have the surfaces covered by pure ice, which is a plausible assumption concerning bodies in the outer Solar system.

Figure 3. Snapshots, viewed from the top in the barycentric reference frame, of dust launched from Nix (in red) and Hydra (in green) for the grains radii 5 and 10 \( \mu \text{m} \). The positions of Charon, Nix and Hydra are also indicated, and the time is shown on the top of each snapshot.
In the absence of any in situ measurements in the KB region, we assume that the size of \( m_{\text{imp}} \) is \( 10^{-8} \) kg, which corresponds to an impactor of \( \sim 100 \) \( \mu \)m in radius. This size resembles most particles found in the innermost zones of the Solar system, nevertheless Landgraf et al. (1999) showed that the constant spatial density detected by Pioneer 10 (between 5 and 18 au from the Sun) strongly indicates the KB as the main source of grains. In fact, their model (dust from KB evolving inwards) reproduces quite well the flux measured beyond 8 au. It is worth to remember that the dust flux at Pluto used here is an extrapolation of the flux observed near 5 out to 18 au (Porter et al. 2010). Besides, there is no strong dependence of the dust production rate on the impactor’s mass. For each order of magnitude \( m_{\text{imp}} \) is lower, the resulting \( M^+ \) is lower by a factor of 1.70.

For such impactors with \( v_{\text{imp}} = 2.6 \) km s\(^{-1} \) result \( Y \sim 100 \). Thus, the sum of the mass production rates composed of particles from 1 to 10 \( \mu \)m is \( \sim 10^{-3} \) kg s\(^{-1} \).

For a steady-state ring its mass is directly proportional to the lifetime (\( T \)) of its particles, \( m = M^+ T \). In order to obtain \( m \) we compute how long the ejected particles, through their respective trajectories, stay in the region of space limited by the orbits of Nix and Hydra. The set of particles was initially distributed from the surface of each satellite (1 particle per degree), then as the grains are produced, actually half of them evolves inwards the considered region. Notably, the density decreases as the grains evolve out or strike a massive body in the system. Thus, the mass of escaping ejecta per time in such region of space is proportional to \( m^+/2 \).

Since different grain sizes have different lifetimes, \( T_1, T_5 \) and \( T_{10} \) represent the time that the initial set of 1, 5 and 10 \( \mu \)m sized particles stay between the orbits of Nix and Hydra. Therefore, \( T \) was weighted by the number of particles and by the time each set of grain size is in a stationary state:

\[
T = \frac{N_1 T_1 + N_5 T_5 + N_{10} T_{10}}{N_{\text{total}}}, \tag{3}
\]

where \( N_s \), which represents the number of particles of radius \( s \), follows the power-law size distribution as described in Section 2.2. Therefore, the effects of including the radiation pressure and the feature of the size distribution are embedded in \( T \) (equation 3). From this we can compare the mass \( m \) with the respective mass obtained through \( \tau \). Finally, this mechanism of dust production is able to generate an accumulated mass of \( m \sim 1000 \) kg.

On the other hand, the mass of a ring with width \( dR \) at distance \( R \) from the planet can be estimated from its normal optical depth given a size distribution of the grains (Colwell & Esposito 1990). This model works pretty well if the release amount of dust is not dynamically destabilized and it populates an area given by \( 2\pi R dR \). Therefore, this is a limitation of our approach; it does not provide a distribution of optical depth in a system. Although it provides a useful constraint on the mass of a dust band associated with both plutonian small moons.

A set of dust particles encompassing the orbits of Nix and Hydra as we can see in Fig. 3, for a radial width \( dR \sim 16000 \) km (the average distance between the satellites assuming circular orbits) at \( R \sim 57000 \) km, has a ring mass of about \( 10^3 \) kg corresponding to an optical depth of \( \tau = 4 \times 10^{-11} \) with a size distribution characterized by grains from 1 to 10 \( \mu \)m. This value is many orders of magnitude fainter than the Jupiter’s tenuous rings, and as predicted by our model is too faint to be detected.

4 DISCUSSION

Even in a distant region such as Pluto’s environment, the effects of the solar radiation pressure have to be considered in order to better estimate the orbital evolution of dust particles. The RP component of the solar radiation dictates the orbital dynamics of the dust by increasing their eccentricities and driving those particles to close encounters with the massive bodies in few years, while the PR drag can be safely neglected in the considered time-scale.

We numerically simulated a set of dust particles perpendicularly launched from the surfaces of Nix and Hydra. These particles are under the gravitational effects of Pluto, Charon, Nix and Hydra and the RP component. Our simplified model assumed an isotropic and constant flux of impactors on the surfaces of both small satellites at the heliocentric distance of Pluto. The released particles, encompassing the orbits of Nix and Hydra, temporally form a wide ring. However, collisions with the massive bodies, mainly due to the effects of the RP component, remove 30 percent of the 1 \( \mu \)m particles from the system in 1 yr.

We found that a very faint dust ring with a normal optical depth of \( \sim (10^{-11}) \) can be maintained by the collisional mechanism. It is
worth to point out that the interplanetary environment in the outer Solar system is not well known. Many assumptions, impactor flux and ejecta yield, for example, have to be made in order to estimate a normal optical depth of a putative ring.

The parameter that directly increases the ring density is $M^\kappa$, which by definition is a function of $F_{\text{imp}}, \kappa$ and the body’s cross-section area. The poor knowledge on the dust environment in the outer part of the Solar system is responsible for the uncertainty in the values of the dust flux and yield. Thiesshenhousen et al. (2002) derived a maximum optical depth of $3 \times 10^{-11}$. They were interested in analysing the dust clouds around each member of the Pluto–Charon binary. In this work we are interested in analysing the accumulation of particles in a region extending from Nix to Hydra’s orbit.

The estimate of $\tau = 5 \times 10^{-6}$ (Stern et al. 2006) was obtained assuming that a fraction of $1/10 \, 000$ of the grains is in the micrometre-sized range and that the mean lifetime of this set is $10^5$ yr. Since the effects of the RP component were not included in their analysis, the mean lifetime of the grains is much longer, consequently the derived optical depth is larger than our model presents. Basically, these two models are different, and $\tau$ is many orders of magnitude shorter here.

Poppe & Horányi (2011) derived a maximum optical depth of $1.94 \times 10^{-8}$ for particles within the range $[1, 10] \, \mu m$ ejected from Pluto, Charon, Nix and Hydra. In their study, Nix and Hydra were the main contributors to a plutonian ring system. They also present the values $8.5 \times 10^{-10}$ and $4.17 \times 10^{-7}$ for the grain sizes from 0.1 to 10 $\mu m$ and from 10 to 100 $\mu m$, respectively. Basically, the difference of the optical depth obtained by Poppe & Horányi and the value derived from our results is due to the dust flux, assumed to be $1 \times 10^{-16}$ here and $2.4 \times 10^{-15} \, \text{kg} \, \text{m}^{-2} \, \text{s}^{-1}$ (Poppe, private communication) and the lifetime of the grains.

A spacecraft carrying a dust detector can help in the reconnaissance of the IDPs populations. The New Horizons mission will offer the best opportunity to obtain in situ measurements of the dust fluxes during all the way and beyond Pluto. It has a dust counter onboard which can detect particles larger than 1 $\mu m$ in radius (Horányi et al. 2008).

In 2011, the fourth plutonian moon (temporarily named P4), was found through observations taken by the Hubble Space Telescope, led by M. R. Showalter and D. P. Hamilton. The satellite is located between the orbits of Nix and Hydra with an estimated diameter ranging from 13 to 34 km, corroborating the results presented in Pires dos Santos, Giuliani Winter & Sfair (2011). In the same set of images no ring around Pluto was detected, which was the main goal of the observing proposal. In their survey, the detection threshold was 10–30 times fainter than the prior limit, enabling the detection of a ring comparable to the major dust rings of the giant planets. One year later, another small satellite was found bound to Pluto in the set of images credited to NASA; ESA; M. Showalter, SETI Institute. It is temporally named P5. Further data concerning P4 and P5, and maybe other moons, will help in the analysis of the dust production and its role in this system.

ACKNOWLEDGEMENTS

The authors wish to thank the referee for the critical reading of this manuscript. We also thank M. Horányi and A. Poppe for constructive discussions. PMP is grateful to FAPESP-2009/1826-2 for financial support. SMGW thanks Fapesp and CNPq for supporting this research, and DCM thanks Fapesp.

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\textsuperscript{1}http://www.nasa.gov/mission_pages/hubble/science/new-pluto-moon.html