Erosion processes affecting interplanetary dust grains

Peter Wurz

Abstract The lifetime of grains in interplanetary space is limited by erosion processes. For grains which are smaller than 1000 nm the lifetimes are severely limited, in particular in the inner solar system, mostly by ion-induced sputtering by solar wind ions. Thus, to maintain a stable population of sub-micron grains inside Mercury's orbit the loss of these grains has to be balanced by a supply of new grains. These grains may have their origin in Sun-grazing comets, decay of larger grains by mutual collisions, and grains released from Mercury's surface by micro-meteorite impacts.

1 Introduction

Grains in interplanetary space are subject to several erosion processes that limit their lifetime. These erosion processes are mainly ion-induced sputtering, photon stimulated desorption and sublimation, with the latter two processes relevant for icy grains and other volatile material contained in the grain. Since the erosion processes act on the surface of a grain and the ratio between surface and volume of a grain becomes larger for smaller grains, the erosion processes become increasingly important for smaller grains, which will lead to a preferential depletion of the smallest grains from the population of grains if this loss is not compensated by a source of such grains.

Here we will review the three major erosion processes and estimate the typical lifetimes of grains. For simplicity we will in the following assume spherical grains in our estimates on the lifetimes of grains controlled by these erosion processes. A variation of grain size distribution because of mutual collisions is not discussed here. For the erosion estimates, we assume that the

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grains stay in a fixed orbital distance R to the Sun. Note that we consider loss of grains in terms of the three mentioned erosion processes, but we do not consider not the loss by destruction, nor the loss of a grain by changing its orbit by as a result of external forces.

Actual trajectories in the interplanetary space can be varied, and their calculation is involved (e.g., Mukai and Yamamoto, 1982). In addition to the gravitational forces non-gravitational forces influence the trajectories of grains. The major non-gravitational forces are the solar radiation force, which can completely compensate the gravitational force for grains below the μm size, and the Poynting-Robertson drag. Solar wind pressure will also act againsts the gravitational pull, and becomes important also only for the smallest grains. Earlier, the orbital lifetime of obsidian grains in Earth orbit was calculated by Mukai and Yamamoto (1982) considering all these forces. These orbital lifetimes are in the range of $30 - 1000$ years for grains of $10 - 1000$ nm size, respectively.

In the following discussion we will distinguish between mineral grains and icy grains. As we will see in later, the volatile fraction of a grain will be lost very fast for small grains in the inner solar system and most of the grains will be reduced to their mineral content. Little is known about the mineral composition of grains in interplanetary space. Different compositions are expected depending on the origin of the grain, e.g. from comets or from the asteroid belt. Silicate grains have been observed in the interstellar media in infrared spectra. However, spectral features indicate that other minerals should be present as well. Also, if the grain's origin is in the asteroid belt a chondritic composition is likely.

For the estimates of sputter erosion we use the mineralogical composition of the regolith of Mercury (Wurz et al., 2010), in the absence of detailed information of the dust composition. This mix of minerals consists of 27% feldspar (mostly anorthite), 32% pyroxenes (mostly enstatite), 39% olivines (mostly fosterite), and about 3% of several other minerals (Wurz et al., 2010). Although of different mineralogical composition, the total sputter yield of the lunar regolith is very similar to Mercury's (Wurz et al., 2007), thus we expect that the sputter yields for mineral grains will be about the same. Also sputtering of magnetite and obsidian grains have been investigated before (Mukai and Schwehm, 1981; Mukai and Yamamoto, 1982).

Water ice grains have a much larger sputter yield for solar wind ions and are also strongly affected by sublimation.

2 Dust erosion by sputtering

Particle sputtering is the release of atoms and molecules from the surface of a solid (e.g. a grain) upon impact of energetic ions or atoms on the surface. The sputter yield is the average number of atoms or molecules removed from the solid per incident particle. Sputtering is a well-studied phenomenon in material science (Behrisch and Eckstein, 2007). Particle sputtering will release all species from the surface into space reproducing more or less the local surface composition on an atomic level in the sputtered flux. Preferential sputtering of the different elements of a compound will lead to a surface enrichment of those elements with low sputter yields in the top-most atomic layers. However, the steady-state composition of the flux of sputtered atoms, thus the erosion of a grain, will reflect the average bulk composition (Betz and Wehner, 1983). Thus, particle sputtering, when operative, will homogeneously erode the entire gain.

The main population of ions relevant for the survival of interplanetary dust grains against sputtering is the solar wind. The solar wind plasma is a mixture of electrons, protons, alpha particles, and heavier multiply charged ions (Wurz, 2005, and references therein). The ions have an average number density of 95% protons and 5% alpha particles, respectively (McComas et al., 2000). Heavy solar wind ions are not important for solar wind induced sputtering because their total abundance is about 0.1% in the solar wind (Mukai and Schwehm, 1981; Wurz et al., 2007). For regular solar wind conditions the solar wind velocities are in the range from $v_{\mathrm{SW}} = 300$ to 800 km s^{-1}, which covers the typical variation of solar wind conditions. In addition, there are coronal mass ejections (CMEs), which are massive and episodic release of solar matter into interstellar space. CME have a larger range in plasma parameters (Wurz et al., 2003; Wimmer et al., 2006). The frequency of CMEs

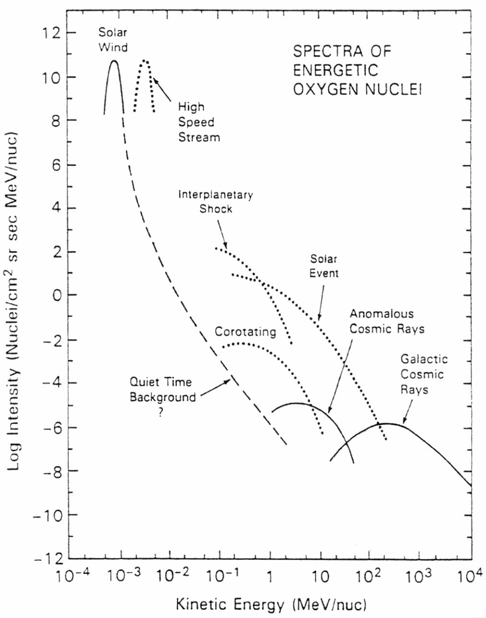

Fig. 1 Typical oxygen differential spectra for different particle populations of interplanetary plasma (Gloeckler and Wenzel, 2001). Proton intensities are about a factor 5000 higher.

correlates with the solar activity cycle (Yashiro et al., 2004; Riley et al., 2006). At higher particle energies there are a range of transient particle populations with smaller intensities at higher particle energies. Figure 1 summarises the energy spectra for particle populations observed in interplanetary space.

Atoms sputtered from a grain may become ionised via charge exchange with the solar wind ions, mostly by the protons. This newly born ions are accelerated by the electro-magnetic fields of the solar wind plasma to become a distinct ion population in the solar wind plasma. Ions introduced into the solar wind plasma flow are called pick-up ions (PUI). PUIs originating from sputtering of dust are referred to as "inner source PUI", and have been detected in the solar wind plasma (Gloeckler et al., 2000). Alternatively, it has been proposed that these inner source PUIs are heavy solar wind ions that pass through a dust particle and become neutralised are singly charged by passing through the grain (Wimmer and Bochsler, 2003). This process will only work for grains smaller than the penetration depth of solar wind ions, i.e., for dust particles smaller than approximately 300 nm. Also a fraction of the neutral solar wind arises from the interaction of the solar wind ions with small dust particles from which the dust column density between the Sun and Earth has been estimated (Collier et al., 2003).

2.1 Sputtering of Mineral Grains

The sputter yields for the difference species of a grain are obtained using the TRIM.SP calculation (Biersack and Eckstein, 1984; Ziegler et al., 1984; Ziegler, 2004) and the recent review on computer simulation of sputtering by Eckstein and Urbassek (2007). TRIM, like many other simulation programmes for sputtering, assume that the collisions between atoms can be approximated by elastic binary collisions described by an interaction potential. The energy loss to electrons is handled separately as an inelastic energy loss.

For typical regolith surface compositions, the total sputter yield, i.e., all species sputtered from the surface taken together, is derived as $Y_{tot} \approx 0.12$ atoms per incoming solar wind ion at 400 km s^{-1}, considering protons and alpha particles only. This sputter yield is the integral over all emission angles and all energies of sputtered particles. For details on the energy and angular distribution of sputtered particles from regolith see Wurz et al. (2007). The 5% alpha particles in the solar wind contribute about 30% to the sputter yield. Earlier, Mukai and Schwehm (1981) estimated the solar wind sputter yield for obsidian and magnetite as 0.03 and 0.04 respectively. CMEs can cause increased sputtering of the grains because their ion density can be much larger than the regular solar. In addition, alpha particles are often enhanced in the CME plasma, which increases the sputter yield even more. The sputter yield is based on the regolith of the Moon and Mercury (Wurz et al., 2007, 2010), which we use here since the mineral composition of the grains is not known sufficiently well, and will be varied. This sputter yield calculation assumes a solid grain; if there were porosity in the grain, it will reduce the sputter yield accordingly (Cassidy et al., 2005).

By coincidence the yield for solar wind sputtering of mineral grains peaks for the typical solar wind ion energies, actually around a specific energy of about 1 keV nuc^{-1}, with a rather flat dependence within the typical the solar wind velocity range (Draine, 1989; Wurz et al., 2007). Figure 2) shows an estimation of the sputter yield for solar wind plasma for a large velocity range based on the theoretical formulation by Betz and Wien (1994). More precise sputter yield can be derived from the TRIM simulation programme. For much higher ion energies the sputter yield becomes very small (Behrisch and Eckstein, 2007). Energetic particles, which occur episodically in the interplanetary plasma as a result of explosive events on the solar surface and which have much lower intensities than the solar wind ions (see Fig. 1), thus cause negligible sputtering of mineral grains.

The sputtering mechanism causes particle release only from the uppermost atomic layers of the grains, i.e., from the top-most surface. At solar wind ion energies the impacting particles penetrate up to a range of 100 nm from the surface of the solid saturating the grains with hydrogen and helium to this depth.

The solar wind flux, $f_{\mathrm{SW}}(R)$, scales inversely with the distance to the Sun, R, as (Slavin and Holzer, 1981; Russell et al., 1988)

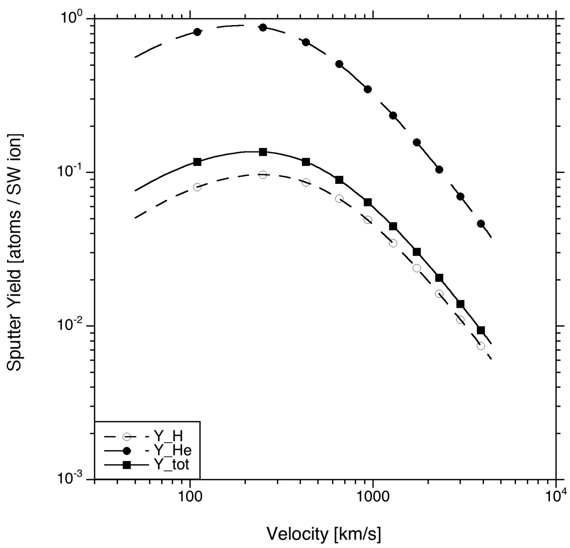

Fig. 2 Estimates of the sputter yield of mineral grains for solar wind sputtering based on (Betz and Wien, 1994). Traces show the individual proton and alpha particle sputter yield, Y_H and Y_{He}, respectively, as well as the composite yield, Y_{tot}, assuming 95% protons and 5% alpha particles.

$$f_{\rm SW}(R) = f_{\rm SW}(R_0)\left(\frac{R}{R_0}\right)^2 \tag{1}$$

where R_0 is the astronomical unit. The solar wind flux is $f_{\rm SW}(R_0) = v_{\rm SW}(R_0)\cdot n_{\rm SW}(R_0)$ with the solar wind number density $n_{\rm SW}$, which at Earth orbit amounts to $f_{\rm SW}(R_0) \approx 8\cdot 10^6$ m^{-3} $\times$ $400\cdot 10^3$ m s^{-1} $= 3.2\cdot 10^{12}$ ions m^{-2} s^{-1}, for typical solar wind conditions in the ecliptic plane (Schwenn, 1990; Wurz, 2005). At larger solar latitudes, about 30° away from the ecliptic plane, the solar wind speed increases to about 800 km s^{-1} and the density decreases to about 2 cm^{-3}, during solar minimum conditions (McComas et al., 2000). This solar wind organisation with latitude becomes much more chaotic during solar maximum conditions (McComas et al., 2008).

For the solar wind flux of $f_{\rm SW}(R_0) = 3.2\cdot 10^{12}$ ions m^{-2} s^{-1} we get a sputtered flux of $f_{\rm SW}(R_0)\cdot Y_{tot} = 3.2\cdot 10^7$ atoms per cm^{-2} s^{-1} from the surface of a mineral grain. This corresponds to a material removal of about 0.13 nm per year in Earth orbit, which is similar to the erosion of Mercury's and the Moon's surface (Wurz et al., 2010). Earlier estimates for the sputter erosion rate of silicates gave a range of 0.01 – 0.02 nm per year (Mukai et al., 2001), and for graphite grains in the solar wind sputter erosion rate was estimated to be 0.005 nm per year assuming a solar wind density of 8 cm^{-3} (Draine, 1989). These earlier estimates are based on a simplified derivation of the sputter yield of solids, which was improved since then (see e.g. Behrisch and Eckstein, 2007). The erosion of a grain by sputtering can be expressed by

$$\frac{d}{dr}(n\ V)\frac{dr}{dt} = -f_{\rm SW}Y_{tot}A \tag{2}$$

which gives the erosion rate

$$\frac{dr}{dt} = -\frac{f_{\rm SW}Y_{tot}}{4n} \tag{3}$$

where r is the grain radius, n is the number density of atoms in the grain, V the grain volume, and A the cross section of the grain. Since the grain will be arbitrarily rotating we can assume that sputtering causes homogeneous removal of material from the entire grain surface, although only a hemisphere is bombarded with solar wind ions at the time. Equation 3 can be easily integrated to derive the erosion time, $t_{\rm SP}$, until a grain of initial size r_{in} is completely consumed by solar wind sputtering:

$$t_{\rm SP}(R) = \frac{4\ n\ r_{in}}{f_{\rm SW}(R)\ Y_{tot}} \tag{4}$$

The erosion time, $t_{\rm SP}$, is a function of heliospheric distance, R. The erosion of the grains is a strong function of distance to the Sun, with the erosion time in the range of years to hundreds of years at Earth orbit and becomes rapidly shorter closer to the Sun. Figure 3 shows the results of this calculation for

1 nm, 10 nm, and 100 nm size using the composition of Mercury's regolith as a proxy for the grains (Wurz et al., 2010).

In this calculation we assume that the sputter yield is independent if grain size r, even for the smallest grains. There are two scenarios for this size dependence: The sputter yield could be higher for smaller grains, because the energy deposited by the impacting ion cannot be distributed and accommodated so effectively in lattice phonons and thus causes an increased release of atoms. Or, on the contrary, the sputter yield could be lower for smaller grains because the impacting ion is not completely stopped in the solid and thus a lower energy is deposited in the grain resulting in a lower sputter yield. In the absence of experimental laboratory data of sputter yield for sub-micron sized grains, or theoretical information, we made the assumption of a constant sputter yield independent of grain size.

2.2 Sputtering of Icy Grains

For solar wind protons the sputter yield of water ice is about a factor 10 higher than for sputtering of mineral grains (Shi et al., 1995), with a sputter yield of ≈ 0.7 water molecules per proton (see Fig. 4). Thus, the corresponding erosion time (see Eq. 4) becomes smaller by a factor of 10, i.e., of the order of weeks to years for 1 nm, 10 nm, and 100 nm size grains. The high sputter yield for ice will render the grains ice-free on the surface.

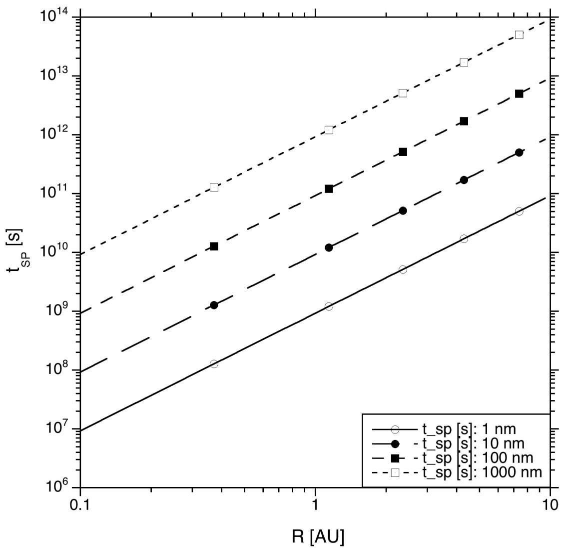

Fig. 3 Lifetime of mineral dust grains against sputtering by solar wind. Calculations are for 1000 nm, 100 nm, 10 nm, and 1 nm grains, lines from top to bottom.

For ice grains the sputter yield increases strongly with the energy of the impacting ion (Shi et al., 1995), unlike the sputter yield of mineral grains, which becomes lower at higher ion energies as discussed above (see also Behrisch and Eckstein (2007)). Thus, if the ice grains pass through a magnetosphere, or originate inside a magnetosphere, with a substantial population of energetic particles, their erosion is much faster.

The lifetime of a 1000 nm ice grain in Saturn's magnetosphere has been estimated as 50 years (Johnson et al., 2008; Jurac et al., 2001), which is much shorter than the 10^6 years a mineral grain would survive in the solar wind at Saturn's distance. Other estimates for 1000 nm size grains inside the Saturnian magnetosphere give a range of lifetimes of 10^2 to 10^4 years (Burns, 1991).

For grains inside the Gossamer rings of Jupiter's magnetosphere, Burns (1991) and Burns et al. (1999) estimated that grains of 1000 nm size have a lifetime of 10^2 to 10^4 years because of sputtering by magnetospheric ions, and a lifetime of 10^4 to 10^6 years for catastrophic fragmentation. The range indicates the uncertainty in the quantitative calculation of the lifetime in the Jupiter system. The erosion rate due to magnetospheric ions in Saturn's magnetosphere is 1 μm year^{-1} (Burns et al., 1999). The corresponding lifetime for sputtering of mineral grains in the solar wind outside Jupiter's magnetospheres for a 1000 nm mineral grain is about 10^6 years (Eq. 4), and about a factor 10 shorter for an icy grain in the solar wind.

3 Dust erosion by evaporation

For a given temperature every solid compound has an associated vapour pressure as function of temperature. In thermodynamics this reflects the equi-

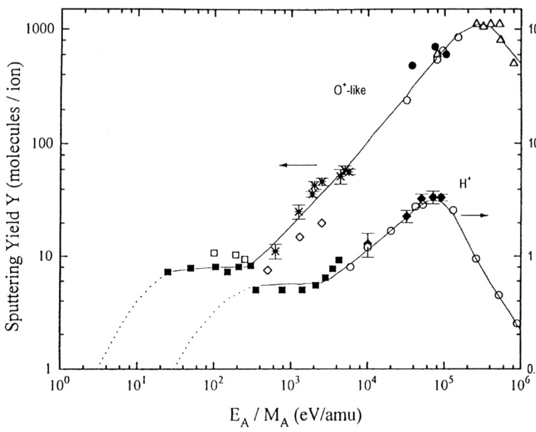

Fig. 4 Compilation of sputter yields of ice for incident protons and oxygen-like ions (from Shi et al. (1995)). Open circles are for H^+, C^+, and O^+; solid circles are for N^+; open triangle for F^{+q}; solid square for H_2^+, and Ne^+; open diamonds for Ne^+; open squares for N^+ and Ne^+; solid diamonds for H^+; asterisks for O^+. Dashed lines are extrapolations based on estimations of the nuclear stopping power.

librium condition between material from the solid entering the gas phase (evaporation) and material from the gas phase condensing at the surface. In interplanetary space, even in the vicinity of a grain's surface, the pressure will be effectively zero (i.e., perfect vacuum), thus any material set free from the surface will be lost to space, which is referred to as sublimation. Here we will consider only the sublimation of water from the grains, sublimation of other species has been discussed in the literature as well (e.g. Mukai et al., 2001). Other volatiles, possibly present in a grain, can be treated with the same formalism. For a perfect vacuum the rate of evaporation, $f_{\rm sub}$, is equal to the rate of molecules hitting the surface, which is given by ideal gas theory as:

$$f_{\rm sub} = \frac{1}{4} n \overline{v} = \frac{p}{\sqrt{2\pi m k_B T}} \tag{5}$$

with the unit (part. / (m^2 s)). In Eq. 5 n is the number density of the vapour, $\overline{v}$ is the most probable velocity, p is the vapour pressure in Pa, m is the molecular or atomic mass in kg, k_B is the Boltzmann constant, and T is the absolute temperature of the grain's surface. For water ice the data for vapour pressure, $p_{\rm vap}$, has been recently reviewed by Grigorieva et al. (2007)

$$p_{\rm vap} = \begin{cases} 3.56 \cdot 10^{12} \exp\left(-\frac{6141.667}{T}\right) & \text{for } T \geq 170 \text{ K} \\ 7.59 \cdot 10^{14} \exp\left(-\frac{7043.51}{T}\right) & \text{for } T < 170 \text{ K} \end{cases} \tag{6}$$

which is given in Pa here. The vapour pressure is a strong function of the temperature. Using the vapour pressure dependence on the temperature (Eq. 6) we can calculate from the sublimation flux (Eq. 5) the lifetime of an ice grain against sublimation

$$t_{\rm sub} = \frac{n_{\rm H_2O}\ \eta\ r_{in}}{f_{\rm sub}(T)} \tag{7}$$

where the surface density of water ice is $n_{\rm H_2O} \approx 9.75 \times 10^{14}$ cm^{-2}, η is the fraction of ice on the surface, and r_{in} is the initial grain radius. Sublimation severely affects the ice loss of small grains, since the grain temperature depends on the heliospheric distance. Moving away from the Sun, there is a certain heliospheric distance beyond which the rate of sublimation is negligible compared to other erosion processes or the orbit lifetime, which is often referred to as the "snow line" (Artymowicz, 1997). The heliospheric distance is approximately at the location of the asteroid belt. Note that there is significant loss of water ice even outside the snow line because of photon stimulated desorption, as will be discussed in the next chapter, and by solar wind induced sputtering.

For smaller objects, for example a 100 nm ice grain at $T = 150$ K (approximately the temperature at the "snow line") is lost already after about 6 μs. At 110 K, about Jupiter's orbit, a 100 nm ice grain will be evaporated after 140 s, at 90 K, about Saturn's orbit, after 6 years. For grains which are a mixture of icy and minerals the time scales for ice loss can become much shorter (Grigorieva et al., 2007). Figure 5 shows the sublimation time derived from Eq. 7 using a simple approximation for the grain temperature, i.e., the equilibrium between absorption of solar light and thermal emission. The dramatic decrease in life time for icy grains for smaller heliocentric distances can clearly be seen.

The temperature of a grain in interplanetary space depends mainly on three parameters (Grigorieva et al., 2007): its size, its mineral composition, and its distance from the Sun. The temperature can be calculated by considering the energy balance between absorbed solar energy and energy loss by re-radiation and sublimation (Mukai and Schwehm, 1981). Grigorieva et al. (2007) performed these calculations for a range of grain sizes and a variety ice-mineral mixtures (see also Li (2011)). Below a grain size of 100 μm size-dependent heating/cooling becomes important, with grains smaller than about 1000 nm being significantly hotter than their larger counterparts. Also the latent heat of sublimation was considered in these calculations. However, Grigorieva et al. (2007) found that at grain temperatures $T \geq 150$ K the effect of the latent heat on the grain temperature becomes negligible. For small grains, in the size range of 1 – 10 nm, Aannestad (1989) calculated that the absorption of a photon increases the temperature of the grain momentarily,

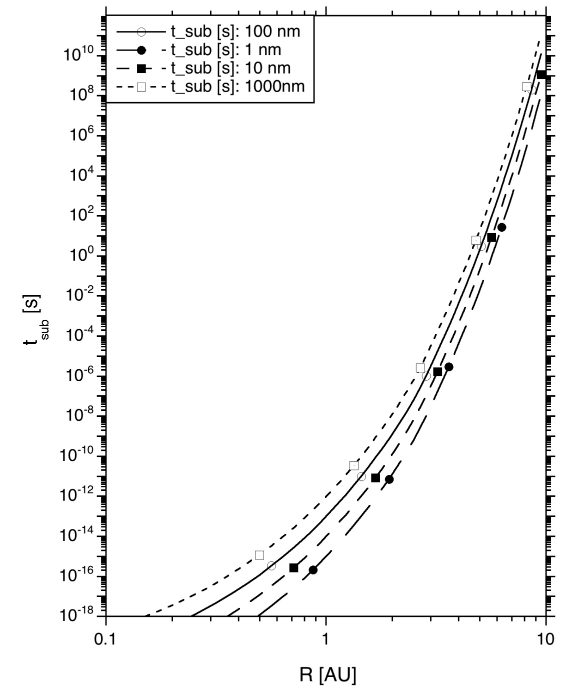

Fig. 5 Lifetime of ice dust grains in seconds against sublimation using Eq. 7. Calculations are for 1000 nm, 100 nm, 10 nm, and 1 nm grains, lines from top to bottom. The temperature of the grains has been approximated by assuming a simple equilibrium between absorption of solar light and thermal emission.

followed by a slow decrease of the temperature with a time constant of the order of 1000 s. For 5 nm grains in the interstellar medium temperature rises in the range of 20 – 50 K will occur upon absorption of a photon.

4 Dust erosion by photon stimulated desorption

Photon-stimulated desorption (PSD), which sometimes is referred to as photon sputtering, is when a photon is absorbed by the surface of a grain and an atom or molecule is released from the surface eventually, via an electronic excitation process at the surface.

We can calculate the flux of photon-stimulated desorption ϕ_i^{PSD} of a species i from the surface by

$$\begin{aligned}\phi_i^{\mathrm{PSD}} &= f_i N_S \int \phi_{ph}(\lambda) Q_i(\lambda) d\lambda \\ &\approx \tfrac{1}{4} \phi_{ph} Q_i f_i N_S\end{aligned} \tag{8}$$

where the factor 1/4 gives the surface-averaged value. ϕ_{ph} is the solar UV photon flux at the grain's surface, Q_i is the PSD-cross section, N_S is the surface atom density, and f_i is the species fraction on the grain surface. The experimentally determined PSD-cross section for Na is $Q_{\mathrm{Na}} = 1 - 3 \times 10^{-20}$ cm^2 in the wavelength range of 400 – 250 nm Yakshinskiy and Madey (1999) and for K the PSD-cross section is $Q_{\mathrm{K}} = 0.19 - 1.4 \times 10^{-20}$ cm^2 in the wavelength range of 400 – 250 nm (Yakshinskiy and Madey, 2001).

PSD is highly species selective, and works efficiently for the release of Na and K from mineral surfaces. PSD is considered the major contributor for the Na and K exospheres of Mercury and the Moon (Killen et al., 2007; Wurz et al., 2010). However, the release Na and K from the mineral matrix is not very important for a significant erosion of the dust grain since it will cease once the surface is void of Na and K.

Water is also desorbed via the absorption of photons, thus PSD plays an important role for icy dust grains. Photon-stimulated desorption of water has been studied in the laboratory (Westley et al., 1995), and the photodesorption yield per incoming photon, $Y_{\mathrm{H_2O}}^{\mathrm{PSD}}$, is temperature dependent

$$Y_{\mathrm{H_2O}}^{\mathrm{PSD}} = Y_0 + Y_1 \exp(-\frac{E}{k_B T}) \tag{9}$$

with $Y_0 = 0.0035 \pm 0.002$, $Y_1 = 0.13 \pm 0.10$, and $E = (29 \pm 6) \times 10^{-3}$ eV Westley et al. (1995), and thus the photodesorption flux is

$$\phi_{\mathrm{H_2O}}^{\mathrm{PSD}} \approx \frac{1}{4} \phi_{ph} f_{\mathrm{H_2O}} Q_{\mathrm{H_2O}}^{\mathrm{PSD}} n_{\mathrm{H_2O}} = \frac{1}{4} \phi_{ph} f_{\mathrm{H_2O}} Y_{\mathrm{H_2O}}^{\mathrm{PSD}} \tag{10}$$

The photodesorption yield given in Eq. 9 has been experimentally determined for Lyman-α photons, i.e., with a photon energy of 10.2 eV. Photosputtering yields comparable to Westley et al. (1995) results have been derived by theoretical modelling of the interaction of photons and icy surfaces, however at photon energies in the range of 8–9.5 eV (Andersson et al., 2006). Since the solar UV spectrum, and the interplanetary UV spectrum as well, is dominated by Lyman-α radiation the experimental values from Westley et al. (1995) are a good choice for quantitative estimates for photon stimulated desorption.

Photon sputtering depends on the UV photon being actually absorbed on the surface, and not being reflected. Grigorieva et al. (2007) showed that the photon absorption of UV photons is very low at longer wavelengths, and only for photons with energies exceeding about 7.5 eV the absorption reaches unity.

With a surface density of water ice of $n_{\mathrm{H_2O}} \approx 9.75 \times 10^{14}$ cm^{-2} we get a cross section $Q_{\mathrm{H_2O}} = Y^{\mathrm{PSD}}_{\mathrm{H_2O}}$ / $N_{\mathrm{H_2O}} = 1.8\times10^{-18}$ cm^2 at 30 K. For typical solar Lyman-α fluxes of $5{\cdot}10^{11}$ cm^{-2} s^{-1} this results in an UV erosion rate of water molecules of $4.4{\cdot}10^8$ cm^{-2} s^{-1}. This corresponds to a water ice removal of about 7.5 μm per year in Earth orbit.

Using Eq. 10 we can estimate the lifetime of an icy grain at a certain heliospheric distance, R, which is

$$t_{\mathrm{UV}}(R) = \frac{4\ n_{\mathrm{H_2O}}\ r_{in}}{\phi_{ph}(R)\ Y^{\mathrm{PSD}}_{\mathrm{H_2O}}} \tag{11}$$

where the photodesorption yield $Y^{\mathrm{PSD}}_{\mathrm{H_2O}}$ is a function of temperature (Eq. 9), which is a function of heliospheric distance R. Figure 6 shows the lifetime against photon stimulated desorption, $t_{\mathrm{UV}}(R)$, for ice grains of 100 nm, 10 nm, and 1 nm radius, for traces from top to bottom, respectively, for temperatures below 80 K, which have to be considered as upper limit since the grains will be warmer at smaller heliospheric distances. Lifetimes of small icy grains against photon sputtering are relatively short; even at Jupiter's orbit the lifetime is about 1 – 100 years for 1 – 100 nm grains, respectively, and decreasing to days to weeks at Earth orbit. Around UV-bright stars the effect of photosputtering will be even stronger Artymowicz (1996) and the position of the actual snow line is no longer determined by sublimation alone.

Desorption yields for water for fast protons and electrons impacting on the icy grain are similar to the PSD yields (Brown et al., 1978, 1980; Heide, 1984; Shi et al., 1995), however, in interplanetary space their fluxes are usually much lower than the Lyman-α fluxes, unless the grain is inside the magnetosphere of giant planet.

5 Conclusions

The lifetime of nano particles in the inner solar system is severely affected by various erosion processes, which can also be seen in the summary given in

Fig. 7. Ion-induced sputtering of grains occurs at all heliocentric distances and becomes increasingly important the closer to the Sun the grain is residing. Inside Mercury's orbit the lifetime ranges from years to weeks, depending on grain size. Since the erosion affects the smaller grains more than the larger grains, the grains size distribution will be altered, with a depletion of the smallest grains. If there is a stable population of small grains inside Mercury's orbit the loss of grains by sputtering has to be balanced by a source of grains. This source of grains could be material released sun-grazing comets, destruction of larger grains, and grains released from Mercury by micro-meteorite bombardment. For example, the production of small dust grains has been identified as an important source process to maintain the dust distribution (Ishimoto, 2000).

Mercurys mass accretion rate is 10.7 – 23.0 tons/day, for Mercurys apocentre and pericentre, respectively (Müller et al., 2002). Recently, Borin et al. (2009) reported a meteoritic flux of 2.382×10^{14} g cm^2 s^1 that corresponds to 1540 tons/day, which is about a factor 80 higher than the earlier estimates. The bodies impacting on Mercury will release matter from its surface, atoms, molecules, up to grains of various sizes, and a certain fraction of this material will leave the gravitational field of Mercury. If we take the latter rate of meteoritic flux and assume that 0.1% of the impacting flux causes the release of 100 nm grains from Mercury, the source flux of these grains would be about $5{\cdot}10^{15}$ grains s^{-1}. Kameda et al. (2007) found a correlation of Na atoms emitted from Mercury's surface and interplanetary dust.

If the grains are composed partly or fully out of ice they are also subject to photon stimulated desorption and sublimation of water molecules. Sublimation is the dominant process for ice loss inside the "snow line" severely

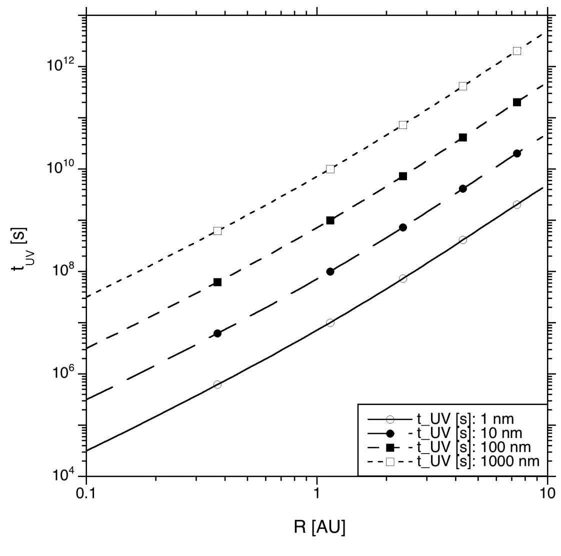

Fig. 6 Lifetime of ice grains against photon stimulated desorption by solar Lyman-α photons. The life is calculated using a simple temperature estimate for the grain temperature for the temperature dependent photodesorption yield (Eq. 9). Calculations are for 1000 nm, 100 nm, 10 nm, and 1 nm water ice grains, lines from top to bottom.

limiting the lifetime of icy grains (see Fig. 7). But even outside the snow line there is erosion of icy grains because PSD is highly effective, at least by a factor 100 more effective than ion sputtering, in removing the ice from the grain. Thus, we can assume that all grains coming directly from the asteroid belt or from the outer solar system to locations inside Earth's orbit will have lost their ice. For grains being initially a mixture of minerals and ice they might become porous after having lost their water ice. However, it was suggested that packing forces produced by anisotropic sublimation of mantle material of the grain will result in compaction of the grain, i.e., an increase in its density (Mukai and Fechtig, 1983). The time scale for such a process was estimated to be $10^4 - 10^5$ years.

Since the lifetime of ice in the inner solar system is very limited, icy grains have to be delivered by a larger object, i.e., a comet, and released in the inner solar system. For example, ice grains have been observed in the coma of comet Hartley 2 (A'Hearn et al., 2011) and have been observed in the plume after the impact of the *Deep Impact* impactor on comet Temple 1 (Schulz et al., 2006).

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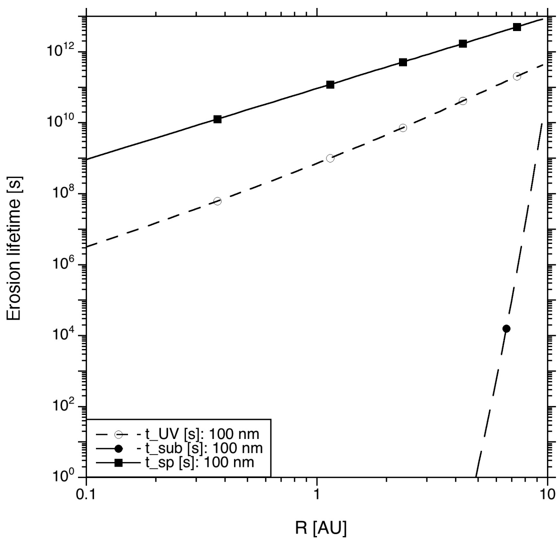

Fig. 7 Comparison of the lifetime of grains against the three erosion processes for 100 nm grains. Data are from the previous figures: sputtering (Fig. 3), sublimation of ice (Fig. 5), and photon stimulated desorption of ice (Fig. 6).

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