DUST PARTICLES AND NON-CATASTROPHIC COLLISIONS

I. Kapišinský
Astronomical Institute of the Slovak Academy of Sciences
842 28 Bratislava, Czechoslovakia

Received 21 September 1989

ABSTRACT. The erosion rate of interplanetary dust target particles is investigated due to two kinds of projectiles acting in non-catastrophic collisions: the impact erosion (abrasion) caused mainly by zodiacal dust particles and corpuscular sputtering, caused by the solar wind particles. It is shown that the rate of the total erosion process depends strongly on the particle sizes which are mainly responsible for the efficiency of the two erosive effects. The mass loss and decrease of a particle size due to impact erosion in dependence on heliocentric distance is evaluated taking into account the concentration and velocities of eroding particles in interplanetary space. The consequences of the erosion process on the lifetimes and dynamics of dust particles are discussed and also compared with other nongravitational effects, mainly with the Poynting-Robertson effect.

1. INTRODUCTION

The interplanetary medium represents a complicated system of bodies with various mechanisms, effects and interrelations which are responsible for the changes of physical and dynamic parameters of a given object. A large number (if not all) of the known effects and mechanisms acting on micrometeoroids and small particles evidently have a nongravitational and dissipative character. In one of the previous paper (Kapišinský, 1984b) the whole set of more than twenty known nongravitational effects was divided into three basic groups: destructive, disruptive and disturbing effects. In principle, all the effects of the first two groups directly cause a loss of mass and decrease in the size of the original larger particles with serious consequences to their dynamics. The first group of destructive effects include continuously acting destructive processes, e.g. impact erosion, corpuscular sputtering, processes of melting, ablation, evaporation and incomplete collisional destruction. Among them, impact erosion has been chosen for more detailed analysis in the present paper with respect to the changes of its efficiency as related to meteoroids with sizes roughly greater than 100 μm. But due to the high efficiency of corpuscular sputtering on micrometeoroids roughly smaller than 100 μm, its influence should also be considered.

It is known that the efficiency of both effects mentioned above and its changes strongly depend on many conditions and factors. Each of them must be considered separately in order to assess the variations of the erosion rate successfully. Therefore, in the following sections we shall concentrate on some aspects of this problem, which can be formulated in the form of the following basic and additional questions:

A – How does the erosion rate depend – on the position of the eroded particle in the heliocentric orbit;

B – How does the erosion rate depend – on the position of the particle orbit in the eroding medium;

B1 – on the density of the eroding medium;

B2 – on the mutual collision frequency

B3 – on the energy of the collisions;

C – What is the combined influence of the impact erosion and corpuscular sputtering?

But first of all we must clearly define the initial conditions and standards.

2. INITIAL CONDITIONS

2i – Impact Erosion at Standard Heliocentric Distance r = 1 AU

By impact erosion (referred to as abrasion in some papers) we understand the process of abrading of the surface layers of a larger meteoroid (target particles) due to collisions with much smaller particles (projectile particles). This type of non-catastrophic collision may be understood as the bombardment of target particles by classical particles of the zodiacal cloud. The dynamical and physical characteristics of these particles (eroding medium), therefore, must be taken into account (dimension, inclination of orbit, spatial concentration, flux, etc.). Assumptions of collision velocity (10 km s^{-1}) as well as estimates of the exposure times for different types of meteoroids, in principle, enable us to determine the values of the impact erosion rate at least at the standard heliocentric distance of about 1 AU. But unfortunately, in the astronomical literature the solution of this special problem is very rarely mentioned. Consequently, this situation complicates the comparison of our results with other ones and this is reflected in the references also. Therefore, we have to draw on the classical work of Whipple (1967). According to him the various exposure ages for iron, stone and cometary particles ($\sim 5\times10^8$; $< 5\times10^7$ and $\sim 10^4$ years, respectively) indicate the following abrasion rates in the neighbourhood of the Earth's orbit: 5×10^{-8}; 5×10^{-7} and about 10^{-4} cm yr^{-1}, respectively. With respect to results of the collection experiments and theoretical analyses (Ceplecha, 1977; Braun et al., 1979; Beech, 1984, etc.), taking into account also other aspects of this problem, we have chosen the value of the annual decrement of radius of about 10^{-6} cm yr^{-1} at heliocentric distance $\sim$ 1 AU as the most acceptable standard. The changes of this standard value will be considered in the following sections.

2ii – Corpuscular Sputtering at r = 1 AU

By corpuscular sputtering we understand the sputtering of the surface layers of the meteoroid due to separate solar wind particles. McDonnell and Ashworth (1972) obtained extremely low values of corpuscular sputtering efficiency, but these are based on studies of the erosion phenomena on the lunar surface and on the sunlit face of meteoroids in interplanetary space with generally adopted values of the solar wind flux. Other authors have used the value 5×10^{-10} cm yr^{-1} (McDonnell, 1971) but also $\sim 5\times10^{-9}$ cm yr^{-1} (Maurette and Price, 1975; Dohnanyi, 1978). Most studies estimate the corpuscular sputtering efficiency at about 4×10^{-9} cm yr^{-1} at a distance of 1 AU (Kresák, 1960; Wehner et al., 1971). In our study this value was taken to be the standard value and constant irrespective of the decreasing size of target particles. This assumption seems to be quite correct, because of the very small and constant radius of the projectile particles (different components of solar wind) which implies a corresponding very high ratio of masses (sizes) of the target and projectile particles. According to Dohnanyi's dynamical studies (1978) the condition of non-catastrophic collisions is, therefore, valid practically over the whole scale of target sizes.

3. CHANGES OF STANDARDS

3i – Changes of Standard During One Revolution

First of all it is necessary to consider whether the rate (efficiency) of impact erosion varies substantially in the course of one revolution of the target meteoroid in a heliocentric orbit of small ellipticity (e = 0.6), i.e. whether the rate of impact erosion depends significantly on minor changes of heliocentric distance, or whether it may be neglected. This problem was considered by the author in his previous papers (Kapišinský, 1980; 1984a) in more detail. In these papers, the erosion effect in the perihelion region P (defined in terms of the true anomaly v as $270^\circ \leq v \leq 90^\circ$) was compared with the erosion effect in the aphelion region A ($90^\circ \leq v \leq 270^\circ$)

under direct motion of the meteoroid along an elliptical orbit with eccentricity e. Using Kepler's 2nd and 3rd laws and the coefficient which expresses the decrease of the target meteoroid radius in region P and A in dependence on the orbit eccentricity, we obtained the following results: For the slightly eccentric and stable orbits ($e \leq 0.6$), the erosion effect in the perihelion and aphelion regions may be considered approximately identical. Thus, the changes of the impact rate over one revolution of the meteoroid along its whole orbit can be considered as negligible and may then be taken as constant. Evidently the impact erosion rate (its change) does not depend as much on the position of the eroded particle in the little elliptical orbit as on the parameters (dimensions) of the orbit itself. With a view to these conclusions, in our further consideration of the erosion effect we can turn our attention to larger changes in heliocentric distance. For circular or nearly circular orbits the parameters a and r may, therefore, also be interchanged.

3ii – Changes of Standards Due to Larger Heliocentric Variations

The target particle in the interplanetary medium undergoes strong physical and dynamical changes. The dynamical changes are characterized by changes of the heliocentric distance. The conditions for the abrasion rate of the target particle should be changed accordingly. We are now considering three effects which may change the erosion rate at the standard distance r = 1 AU (symbol VE_1). Generally, the change of the radius (symbol ds_E) during exposure time T_E due to the impact erosion at any heliocentric distance r acting with efficiency VE_r can be expressed as

$$ds_E = VE_r . T_E = VE_1 . r^{-K} . r_1^{K} . T_E \ , \qquad (1)$$

where $VE_1 = 10^{-6}$ cm yr^{-1} is the standard efficiency of impact erosion according to the conclusion of Section 2i. The value of exponent K represents the rate of the change of the efficiency of impact erosion with heliocentric distance. This change is the results of superposition of several effects. We shall concentrate on three of them, which we shall denote k_1, k_2 and k_3, and which can be expressed as a function of heliocentric distance r. Consequently, exponent K can be expressed as: $K = k_1 + k_2 + k_3$.

Component k_1 represents the idealized case, when the impact erosion rate would only depend on density (spatial concentration) of the eroding medium. If the eroding medium is represented mainly by the dust population of the zodiacal cloud, k_1 should describe the increase in rate VE_r with decreasing heliocentric distance, as indicated by direct space experiments and also indirect measurements in the inner regions of the Solar System. In spite of some discrepancies concerning the value of k_1 (see Hindley, 1976; Link and Rahe, 1976; Leinert et al., 1978; Stanley et al., 1979; Cook, 1978; Leinert et al., 1981, etc.), the value $k_1 = 1.3$ seems to be most acceptable.

The second effect, k_2, is the collision frequency, i.e. the flux of eroding particles. Taking into account the conclusion of Section 3i, assuming only circular or slightly eccentric orbits of dust particles ($r \cong a$), and using the approximation of the energy integral (this also applies to the estimate of component k_3), we obtain a different dependence on heliocentric distance r^{-k_2}, because the particle flux is proportional to their velocity V which, according to the approximated energy integral is proportional to $r^{-0.5}$. Consequently, we may put $k_2 = 0.5$.

Finally component k_3 expresses the fact that the erosion rate also depends on the particle energy $\sim mV^2$. The energy integral for this case indicates a dependence on r^{-k_3} and we may thus put $k_3 = 1$. On the whole, therefore, exponent K in Eq. (1) has a value of at least $K = 1.3 + 0.5 + 1 = 2.8$. (For more details see Kapišinský, 1984a.)

4. SOME NUMERICAL RESULTS AND THEIR DISCUSSION

To interprete the considerations mentioned above, we have calculated some of the values according to Eq. (1). The programs for the individual computations were written for a Wang 2200 C computer in its basic program language. The quantitative results are given in the following tables I and II which concern only the effect of impact erosion for circular orbit, without the corpuscular sputtering effect.

Table I

Time of total destruction (years)

Radius of orbit (AU)	Initial radius of target particle s_o (μm) 1	5	10
0.50	4.35	71.79	1.44×10^2
1.00	1.00×10^2	5.00×10^2	1.00×10^3
1.50	3.12	1.56×10^3	3.12
2.00	6.96	3.48	6.96
2.50	1.30×10^3	6.50	1.30×10^4
3.00	2.17	1.08×10^4	2.17
3.50	3.34	1.67	3.34
4.00	4.85	2.43	4.85
4.50	6.75	3.37	6.75
5.00	9.06	4.52	9.06

The main conclusion concerning the impact erosion may be seen in the fact that, e.g., all physical changes take place over a relatively very short interval of time as compared with time required for the decay of a particle due to complete spiralling of the particle into the Sun according to the relations derived from the classical Poynting-Robertson theory. This can be simply demonstrated by comparing the time of total destruction of particles due to impact erosion (symbol T_{IE}) with the times required for a particle to spiral from its original circular orbit with heliocentric radius r = 5 AU (symbol T_{PR}^{5}) and r = 1 AU (symbol T_{PR}^{1}) to the Sun as a result of the classical Poynting-Robertson effect. The results for particles with density ρ = 1 g cm^{-3} and different original radii s_o (in micrometers) are given in Table III.

Table II

Decrease of target meteoroid radius (cm)

Radius of orbit (AU)	Exposure time T_E (years)				
	1	5	12	30	80
0.50	6.96×10^{-6}	3.48×10^{-5}	8.36×10^{-5}	2.09×10^{-4}	5.57×10^{-4}
1.00	1.00	5.00×10^{-6}	1.20	3.00×10^{-5}	8.00×10^{-5}
1.50	3.21	1.61	3.86×10^{-6}	9.64×10^{-6}	2.57
2.00	1.43×10^{-7}	7.18×10^{-7}	1.72	4.31	1.15
2.50	7.69×10^{-8}	3.84	9.22×10^{-7}	2.31	6.16×10^{-6}
3.00	4.61	2.31	5.54	1.38	3.69
3.50	3.00	1.50	3.60	8.99×10^{-7}	2.40
4.00	2.06	1.03	2.47	6.19	1.65
4.50	1.48	7.41×10^{-8}	1.78	4.45	1.19
5.00	1.10	5.52	1.32	3.11	8.83×10^{-7}

Table III

Comparison of T_{PR} times vs. times of total destruction at r = 1 AU and at r = 5 AU

r = 1 AU			r = 5 AU		
s_o (μm)	T_{IE} (years)	T_{PR}^{1} (years)	s_o (μm)	T_{IE} (years)	T_{PR}^{5} (years)
1	100	704	1	9 060	17 600
5	500	3 520	5	45 200	88 000
10	1 000	7 040	10	90 600	176 000

In our considerations, we have introduced a number of simplifications which may affect the main conclusions of the study of impact erosion. For example, in deriving coefficient K, the relative velocity of the eroding particles with respect to the eroded particle was replaced by their heliocentric velocity. This is based on the statistical assumption that the directional distribution of the relative flux is independent of the heliocentric distance of the eroded particle. Since our knowledge of orbits of interplanetary particles is based nearly exclusively on observations at distance r = 1 AU, we are unable to determine the degree to which the assumption approximates reality.

As regards the assumptions made in deriving the actual value of exponent

K, it should be added that they were chosen to render the value K = 2.8 minimum. Under real conditions the effect of impact erosion would apparently be greater. On the other hand, from the physical point of view, it is possible to consider, whether a certain duplicity was not involved in deriving components k_1, k_2, k_3.

5.THE COMBINED INFLUENCE OF IMPACT EROSION AND CORPUSCULAR SPUTTERING EFFECTS

This influence (which may be referred to as "double erosion") is in some sense beyond the scope of the present paper. In spite of this, we shall shortly mention double erosion due to its important role in considering the changes of erosion rate, on the larger size scale of target particle, i.e. below a limit of roughly 100 μm (corpuscular sputtering regime) and above this limit (impact erosion regime).

As mentioned in the Introduction, in the target size range $\leq$ 100 μm, corpuscular sputtering plays the dominant role in the abrasion process. One may assume that this is, first of all, because catastrophic collisions attenuate the importance of impact erosion at a particular critical ratio of the target and projectile masses. Using empirically introduced relations, Dohnanyi (1978) determined the region in which impact erosion predominates and the region of sizes (masses) of eroded particles in which collisions with projectile particles already have catastrophic consequences. In solving these problems we come up with several problematic points, e.g., of determining reliably the critical boundary of the target particle size, below which one should expect mostly catastrophic desintegration of the investigated particles. Apart from this obscure limit of target particles (may be $\sim$100 μm) it is possible to investigate the double erosion usefully.

More details about discrepancies in this field, modelling and concrete results of more complicated double-erosion mechanisms was presented by author (Kapišinský, 1987).

In this paper three regimes of the double erosion efficiency were distinguished according to the value of the ratio of target and projectile masses (sizes). According to the initial physical characteristics of colliding particles, the double erosion rate was computed on a large micrometeoroid size scale also for three models (1, 2, 3). It is most interesting to compare our results concerning the destruction effect due to double erosion with the Poynting-Robertson inspiralling times. Assuming the initial particle's circular orbit radius, for simplicity, to be r_o = 1 AU, particle density $\sim$3.5 g cm^{-3} and its initial particle radii to be 100, 50, 10, 1, 05 and 0.1 μm, we obtained the results summarized in Table IV, where symbols T_1, T_2, T_3 represent three times of total destruction in the models (1, 2, 3) mentioned above. It must be pointed out that the calculation of double erosion rates was, in this case made, for simplicity disregarding the power law according to Eq. (1) investigated in Section 3ii for impact erosion.

Table IV

Comparison of lifetimes T_{PR}^{1} vs. T_1, T_2 and T_3 (in years)

Initial radius of target particle (μm)	T_{PR}^{1}	T_1	T_2	T_3
100	246 000	2.33×10^{6}	5.58×10^{5}	2.10×10^{4}
50	123 000	1.22×10^{6}	4.65×10^{5}	1.59×10^{4}
10	25 000	2.47×10^{5}	1.79×10^{5}	1.22×10^{4}
1	5 500	2.50×10^{4}	2.47×10^{4}	7.12×10^{3}
0.5	1 200	1.25×10^{4}	1.25×10^{4}	5.02×10^{3}
0.1	200	2.49×10^{3}	2.57×10^{3}	2.17×10^{3}

According to the presented results we can conclude that, for dust particles with an initial radius of 50 to 100 μm, the time of total destruction due to double erosion is of the same order as the Poynting-Robertson inspiralling time T_{PR}^{1} for model "2", about one order larger than T_{PR}^{1} for model "1" and about one order smaller than T_{PR}^{1} for model "3". Double erosion is thus most significant in the investigated range of particle radii for model "3". For initial particle radii of 0.5 to 100 μm the corresponding T_{PR}^{1} time is comparable with time T_3 for model "3"; for the "1" and "2" models, the corresponding T_{PR}^{1} times are shorter. Other conclusions can be drawn from the results presented.

Generally speaking, impact erosion and corpuscular sputtering, acting separately or together, seem to be the equivalent alternative of particle decay, i.e. to total hyperbolic escape, inspiralling in the solar corona, etc. Naturally, all these physical changes of the state of the investigated particle, have serious consequences not only with regard to the lifetimes of particles, but also to their dynamics. However, this aspect of the micrometeoroid problem has been considered elsewhere (e.g. Kapišinský, 1980; 1983). There remain, of course, many effects of a random and disruptive nature (e.g. the windmill effect, Radzievsky effect, electrostatic explosion, corpuscular breakup, evaporation and sublimation effects, chemical breakup, etc.) which can be very significant in the particle's dynamic and physical history. In future, more rigorous investigation of these effects should be taken into account.

REFERENCES

Beech, M.: 1984, Monthly Notices Roy. Astron. Soc. 211, 617.

Braun, G., Dalmann, B.K., Fechtig, H., Grun, E., Kissel, J., Pailer, N.: 1979, Meteoritics 14, 358.

Brownlee, D.E.: 1979, Rev. Geophys. Space Phys. 7, 1735.

Ceplecha, Z.: 1977, in Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins (Ed. A.H. Delsemme; University of Toledo), 143.

Cook, A.F.: 1978, Icarus 33, 349.

Dohnanyi, J.S.: 1978, in Cosmic Dust (Ed. J.A.M. McDonnell, Chichester), 567.

Hindley, K.: 1976, New Sci. 72, 16.

Kapišinský, I.: 1980, Thesis (in Slovak).

– : 1983, Bull. Astron. Inst. Czechosl. 34, 167.

– : 1984a, Bull. Astron. Inst. Czechosl. 35, 300.

– : 1984b, Contr. Astron. Obs. Skalnate Pleso 12, 99.

– : 1987, Bull. Astron. Inst. Czechosl. 38, 7.

Kresák, L.: 1960, Bull. Astron. Inst. Czechosl. 11, 1.

Link, H., Rahe, J.: 1976, in Earth and Extraterrestrial Sciences, IAU Colloquium 31, 259.

Leinert, C., Hanner, M., Link, H., Pitz, E.: 1978, Astron. Astrophys. 64, 119.

Leinert, C., Richter, I., Pitz, E., Plank, B.: 1981, Astron. Astrophys. 103, 177.

McDonnell, J.A.M.: 1971, Space Research 11, 415.

McDonnell, J.A.M., Ashworth, D.G.: 1972, Space Research 12, 333.

Maurette, M., Price, P.: 1975, Sciences 187, 121.

Stanley, J.E., Singer, S.F., Alvarez, J.M.: 1979, Icarus 37, 457.

Wehner, G.K., Ken Knight, C.E., Rosenburg, D.L.: 1963, Planet. Space Sci. 11, 885.

Whipple, F.L.: 1967, in The Zodiacal Light and the Interplanetary Medium (Ed. J.L. Weinberg), NASA SP-150, 409.