Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2023, 17(6), 388–393
https://doi.org/10.12913/22998624/175312
ISSN 2299-8624, License CC-BY 4.0

Received: 2023.10.18
Accepted: 2023.11.07
Published: 2023.11.23

Prediction of Size of Iron Spherules Formed from Melted Micrometeoroids

Wiesław Z. Polak[1]

[1] Department of Applied Physics, Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 38, 20-618 Lublin, Poland
E-mail: w.polak@pollub.pl

ABSTRACT

Movement of liquid iron micrometeoroid in the Earth atmosphere is simulated to find the time-dependence of its acceleration, velocity and coordinates as well as the length of luminous trajectory when the micrometeoroid is still melted. In the simulations it is assumed that the maximum size of the stable droplet is determined by aerodynamic fragmentation of the moving droplet occurring when the Weber number exceeds its critical value. Two different initial altitudes h of droplet formation were analysed: 80 km and 50 km, both for a wide range of initial velocities between 6 and 20 km/s. Depending on their initial velocity, exceeding the Earth's escape velocity equal 11.2 km/s, the maximum radius of solid spherules, emerging from solidified final droplet, is predicted here to lie between (a) 55 and 100 µm for h = 80 km, and (b) 10 and 30 µm for h = 50 km.

Keywords: liquid micrometeoroids, iron spherules, aerodynamic fragmentation, Weber number, froplet size.

INTRODUCTION

For over a century spherical microparticles, also called spherules, are the subject of scientific investigations. They were found in sedimentary geological layers [1, 2], in volcanic rocks [3], at the bottom of the ocean [4] or in marginal part of the polar ice cap [5]. Among them, spherules having magnetic properties [1-4], which make their extraction easier from the surrounding material by applying strong magnets, have drawn special interest. In view of the observed physical and chemical properties of these magnetic particles, some researchers have claimed their extraterrestrial origin [1, 2, 4-6], while others have concluded that they are of volcanic origin [3, 7]. The situation is indeed complicated due to the fact that industrial activities of people in areas, such as welding, metallurgy or coal power plants, also lead to the production of similar spherical microparticles [1, 4, 8-10].

Magnetic spherules found in volcanic deposits, described by Grebennikov [3], throw doubt on the inequivocal interpretation of cosmic origin of other similar objects. Their common feature is a small amount or lack of nickel, the presence of which is characteristic for metallic meteoroids. In another paper [2], the lack of nickel does not prevent the authors to classify them as residues of cosmic particles. Investigation of the chemical composition of 20 different spherules from various regions of the world by Grachev [1], leading to detection of nickel, confirms their cosmic origin. However, in the case of ambiguous results of such analysis, it seems to be necessary to include analysis of size and shape of the spherules because movement of their molten mass in the Earth atmosphere can have an influence on microdroplet geometry.

The aim of the present study is to determine the maximum size of the spherule from simple computer simulations of a microparticle flight in the Earth atmosphere, accompanied with aerodynamic criterion describing droplet stability.

SIMULATION

Simulation of the flight of a liquid iron microparticle in the Earth atmosphere was carried out to determine its final size. The final solid microparticle is attained when its velocity v, decreasing due to air drag forces, is too low to keep heating up of the particle to its melting temperature because an aerodynamic splitting/fragmentation of the particle is generally possible only in case of its molten state. From an analysis of the plot, presented recently by Moilanen et al. [11] and showing physical phenomena related to a meteoroid entering the atmosphere, it can be deduced that the meteoroid ablation ceases just after luminous trajectory end. The authors [11] argued that the observed terminal velocity of a glowing meteoroid able to survive the flight is in the range of 2–4 km/s, and they assume this value to be 3 km/s in their simulations, when the terminal velocity is not available from observations. Following these authors, in the present work we also assume the terminal velocity v_t = 3 km/s for our iron droplet.

The microdroplet formation is attributed here to one of the processes: (i) complete melting of a solid micrometeoroid/microparticle entering the atmosphere, or (ii) ablation of a liquid surface of a larger meteoroid. The fast moving droplets so formed are subjected to the combined action of two forces: (i) cohesion forces (related to the surface tension σ) which tend to maintain a spherical shape, and (ii) dynamic drag forces which tend to deform the droplet and to tear it into smaller parts/droplets. The possibility of a loss of the shape stability is estimated in the literature [12, 13] by using the dimensionless Weber number defined as:

$$We = \frac{\rho_a \cdot v^2 \cdot r}{\sigma}, \qquad (1)$$

where: ρ_a – the density of ambient medium (here the Earth atmosphere at a height h);
v – the actual value of the droplet velocity;
r – the actual radius of a spherical droplet;
σ – the surface tension of a droplet material.

In the literature (e.g. [13]), the Weber number is often defined by the droplet diameter d instead of the radius r; this must be taken into account when comparing the used values of We. An initiation of the aerodynamic fragmentation of the moving droplet occurs when the Weber number exceeds its critical value reported to be: $We_c = 6$ for water droplets [12] or $We_c \approx 9$ for ethyl alcohol drops [13]. In the latter case, the diameter d, instead of the radius r, is used in the above definition in the form of Eq. (1). We assume in our simulation model that fragmentation of an analysed iron microdroplet occurs immediately just after the actual droplet radius r is larger than a maximum radius of a stable droplet

$$r_{stab} = \frac{We_c \cdot \sigma}{\rho_a \cdot v^2}, \qquad (2)$$

which is calculated from Eq. (1). In the simulations presented below it is assumed that, during the movement of a droplet of $r > r_{stab}$, in each case the dynamical forces tear the redundant droplet material off and leave the maximum droplet of the radius r_{stab}.

To calculate the maximum radius r_{stab} of a moving liquid droplet from Eq. (2), it is necessary to know the velocity v by solving numerically the basic dynamic equation in the form taken from the extended abstract presented by Bakhtin et al. [14]:

$$m\frac{dv}{dt} = -\Gamma \cdot S \cdot \rho_a \cdot v^2, \qquad (3)$$

where: m – the actual mass of the microparticle moving with velocity v;
dv/dt – the negative acceleration (i.e. deceleration) of the moving particle;
$\Gamma = 0.05$ [14] – a parameter which corresponds to one half of the drag coefficient C_d when Eq. (3) is compared with the standard formula expressing the air drag force $F_d = ½ C_d \cdot \rho_a \cdot S \cdot v^2$ (used e.g. by Moilanen [11]);
$S = \pi r^2$ – the cross-section area of the particle.

The density ρ_a of the Earth atmosphere decreases with an increase of the distance from sea level and is calculated here from the simple equation

$$\rho_a(h) = \rho_a(0)\exp(-h/H_{atm}), \qquad (4)$$

where: h – the height over the sea level;
$\rho_a(0)$ – the atmosphere density on the sea level taken here to be 1.225 kg/m^3;
H_{atm} = 7400 m [15] – a parameter calculated from the basic thermodynamics knowing that the atmosphere temperature is well approximated by the value of 250 K along the entire height of the atmospheric air column up to 80 km.

Eq. (4) was deduced from a formula expressing the atmospheric pressure, used in the book of Popkiewicz et al. [15], which is valid up to h = 80 km. To complete the calculation from Eq. (3), it is necessary to use the obvious dependence $m = 4\pi r^3\rho/3$, where $\rho = 7874$ kg/m^3 is the density of the iron particle.

The time-dependence of the droplet velocity $v(t)$ as well as its coordinates $x(t)$ and $y(t)$ are the result of a numerical solution of Eq. (3) using simple Euler method with three initial meteoroid parameters: initial height h_0 and initial velocity v_0 inclined at an angle α to the vertical direction. Therefore, horizontal and vertical components of the initial velocity are: $v_{0x} = v_0\sin\alpha$ and $v_{0y} = -v_0\cos\alpha$, respectively, where, following Ref. [14], it is assumed that $\alpha = 48.2^o$. The Euler method is able to predict the values of $v_x(t)$ and $v_y(t)$ as well as $x(t)$ and $y(t)$ at time $t = i\Delta t$ where i is an integer and $\Delta t = 0.02$ s is the time step used in the simulations. When the maximum radius $r_{stab}(t)$ of a stable droplet, calculated using the actual velocity $v(t)$ of the droplet, the actual atmosphere density $\rho_a(h)$ and the constant value of surface tension for iron $\sigma = 1$ J/m^2 [12], is lower than the current radius of the droplet $r(t)$, it is always assumed that $r(t + \Delta t) = r_{stab}(t)$.

RESULTS AND DISCUSSION

The simulated flight of a liquid iron microparticle of the initial radius 250 μm, corresponding to maximum diameter 500 μm of iron droplet as obtained by Čapek et al. [16] in their analysis of observation data, is initiated at two analysed altitudes: 80 km and 50 km. The first one is more realistic when we analyse the microparticles entering the atmosphere from the outer space, because the meteors so formed are observed to be initiated at an altitude of 80–90 km [11] or 78–90 km [16]. Moreover, Bakhtin et al. [14] calculated that meteoric iron particle of radius 250 μm melts at the altitude 80 km. The altitude 50 km is applicable to droplets torn off a larger meteoroid whose surface is melted, due to a high velocity exceeding 3 km/s, and is losing its material by the ablation mainly in the form of a liquid iron removal [16]. The analysed initial velocity v_0 of the particle is extended from a reasonable value in the range from the Earth escape velocity 11.2 km/s up to 20 km/s (well correlating with values given by Čapek et al. [16] and Moilanen [11]) down to a rather theoretical value of 6 km/s, applicable to ablated droplets at the altitude 50 km or any man-made artificial small objects. Since the drag forces acting on the droplet are much higher than the gravity force (compare the values of acceleration from Figure 1a with the acceleration due to gravity $g = 9.81$ m/s^2) the role of gravity force is neglected in the simulations. The extreme and non-monotonic change in the acceleration is explained by three important factors: (i) increasing density of the atmosphere during the flight, (ii) decreasing value of the droplet velocity (Fig. 1b), and (iii) a decrease in the droplet radius (inset in Fig. 1b) limited from above by the maximum radius r_{stab} calculated from Eq. (2). Relatively high values of negative acceleration (deceleration), visible even at the end of plotted curves when the droplet solidifies, denotes the presence of large inertia forces acting on liquid material, which might result in a displacement of materials/admixtures of different densities, if they exist. As is visible from the inset, the loosing of droplet material to reduce its radius is initiated at a certain moment of the droplet flight when its velocity is too high at the actual atmosphere density and the droplet is aerodynamically unstable.

As seen from Figure 2a, the trajectory (which is linear due to omission of the gravity acceleration g) is much longer when the microdroplet is simulated to start in a higher altitude than it is in the case of $h = 50$ km. The time of flight t_f of the melted particle, measured up to attaining $v = 3$ km/s, is very different for $h = 50$ km and 80 km, and is: 1.88 s for $v_0 = 6$ km/s and 0.36 s for $v_0 = 20$ km/s at the lower altitude, compared with 10.24 s for $v_0 = 6$ km/s and 4.04 s for $v_0 = 20$ km/s at the higher one (the latter two values can be read off from Fig. 1b). From Figure 2a it is interesting to note that the length of the flight trajectory is very different only in the case of the lower altitude. The prolonged trajectory marked by dashed line corresponds to the flight of a solidified and stable in size meteoroid until attaining the velocity close to that of sound in the air (i.e. 400 m/s).

The maximum droplet sizes, shown using the same scale in Figure 2a, decreases with an increase in the initial particle velocity. The precise results of the radii of the final droplets, collected in Figure 2b, show that the final radius is highly dependent on the initial velocity of a droplet and its initial altitude. Though one can see several final radii exceeding 100 μm for the lowest analysed velocities, the more realistic meteoroid velocities (i.e. higher than the escape velocity 11.2 km/s) are significantly lower; they lie between 55 and 100 μm for $h = 80$ km, and between 10 and

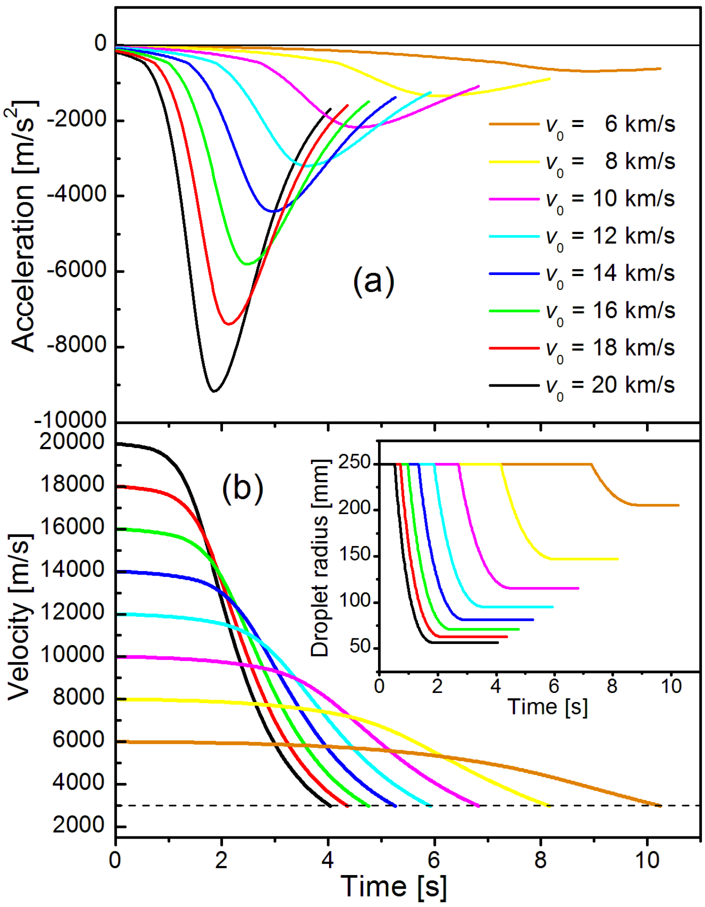

Fig. 1. (a) Time-dependence of acceleration of the simulated iron droplet, initiating its motion in the Earth atmosphere at the height 80 km, until it attains the limiting velocity of 3 km/s. (b) Dependence of the droplet velocity on time during its simulated flight. The dashed line shows the value of 3 km/s which is taken as the lower limit of the velocities sufficient to heat the micrometeorite to the liquid state. In inset plots of the stable droplet radius against their flight time are shown

30 μm for h = 50 km. It should be mentioned that, at a given initial velocity, formation of a particle with a radius smaller than that mentioned above or shown in Figure 2b is acceptable because they may be formed from the material tear off the unstable droplet.

CONCLUSIONS

The simulation model, with the used parameters, excludes the formation of iron particles of diameter larger than 200 μm what is caused by an aerodynamic instability of fast moving liquid micrometeoroid. This conclusion is applicable for droplets formed in the Earth atmosphere at altitudes between 50 and 80 km and moving with initial velocity exceeding the Earth escape velocity. Apart from the elemental composition analysis, comparison of the measured radii of iron or magnetite particles/spherules with these results can be an additional criterion to classify their origin into cosmic or terrestrial. Since the values of an acceptable maximum radius of spherule depends on the Weber number and the drag coefficient, determination of their values for iron droplets moving in the air with a high velocity would be very useful.

Acknowledgements

The author is grateful to Prof. Keshra Sangwal for critical reading of the manuscript. This research was financed under the framework of the project Lublin University of Technology - Regional Excellence Initiative, funded by the Polish Ministry of Science and Higher Education (contract no. 030/RID/2018/19).

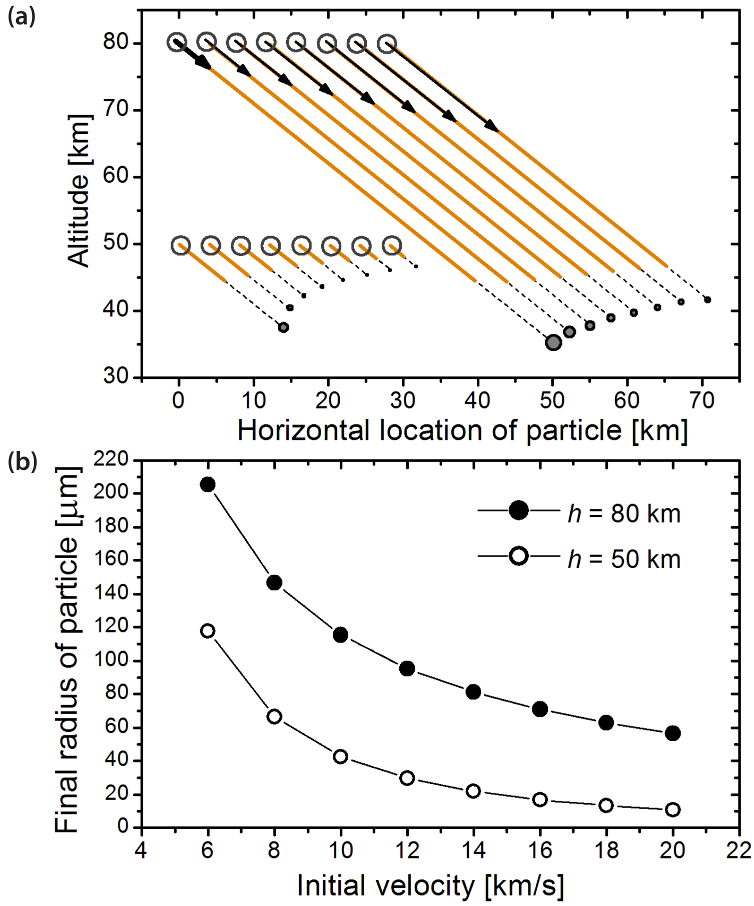

Fig. 2. (a) Flight trajectory and final size of a microparticle of the initial radius 250 µm (all shown in a scale) starting to be melted in the atmosphere at the height 50 km and 80 km. The orange colour shows luminous part of the trajectory, i.e. meteors, connected with the melted state of the particle/meteoroid, while dashed line is its trajectory continued up to attaining the velocity 400 m/s. The analysed initial velocity is increased gradually by 2 km/s from 6 km/s up to 20 km/s from left to the right of the shown trajectories, what is illustrated by the length of the velocity vector for h = 80 km. (b) Dependence of the final microdroplet radius on the initial velocity of the particle entering the atmosphere

REFERENCES

1. Grachev A.F., Korchagin O.A., Tselmovich V.A., Kollmann H.A. Cosmic dust and micrometeorites in the transitional clay layer at the Cretaceous–Paleogene boundary in the gams section (Eastern Alps): Morphology and chemical composition. Izvestiya, Physics of the Solid Earth 2008; 44: 555-569.
2. Korchagin O.A. Metallic microspheres and microparticles in lower Cenomanian sediments of the Crimea: Evidence for the cosmic dust event. Doklady Earth Sciences 2010; 431(2): 441-444.
3. Grebennikov A.V. Endogene spherules of Cretaceous-Paleogene ignimbrite complexes of Yakutinskaya volcane-tectonic structure (Primorye). Proceedings of the Russian Mineralogical Society 2011; 140(3): 56-68.
4. Pettersson H., Frederiksson K. Magnetic spherules in deep-sea deposits, Pacific Science 1958; 12: 71-81.
5. Khisina N.R., Badyukov D.D., Wirth R. Microtexture, nanomineralogy, and local chemistry of cryptocrystalline cosmic spherules. Geochemistry International 2016; 54: 68-77.
6. Szöőr G., Elekes Z., Rózsa P., Uzonyi I., Simulák J., Kiss Á.Z. Magnetic spherules: Cosmic dust or markers of a meteoritic impact? Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 2001; 181(1-4): 557-562.
7. Sungatullin R.H., Bakhtin A.I., Sungatullina G.M. Tsel'movich V.A. Glukhov M.S. Osin Y.N., Vorobiev V.V. Composition and morphology of metal microparticles in Paleozoic sediments of Caspian depression. International Journal of Applied Engineering Research 2015; 10(24): 45372-45382.
8. Zhang H., Shen S.Z. Cao C.Q., Zheng Q.F. Origins of microspherules from the Permian–Triassic boundary event layers in South China. Lithos 2014; 204: 246-257.

9. Kirichenko K.Y., Drozd V.A., Chaika V.V., Gridasov A.V., Kholodov A.S., Karabtsov A.A., Golokhvast K.S. Nano-and microparticles in welding aerosol: electronic and microscopic analysis. Physics Procedia 2017; 86: 54-60.
10. Stankowski W.T.J., Katrusiak A., Budzianowski A. Crystallographic variety of magnetic spherules from Pleistocene and Holocene sediments in the Northern foreland of Morasko-Meteorite Reserve. Planetary and Space Science 2006; 54(1): 60-70.
11. Moilanen J., Gritsevich M., Lyytinen E. Determination of strewn fields for meteorite falls. Monthly Notices of the Royal Astronomical Society 2021; 503(3): 3337-3350.
12. Wacheul J.B., Le Bars M., Monteux J., Aurnou J.M. Laboratory experiments on the breakup of liquid metal diapirs. Earth and Planetary Science Letters 2014; 403: 236-245.
13. Flock A.K., Guildenbecher D.R., Chen J., Sojka P.E., Bauer H.J. Experimental statistics of droplet trajectory and air flow during aerodynamic fragmentation of liquid drops. International Journal of Multiphase Flow 2012; 47: 37-49.
14. Bakhtin A.I., Sungatullin R.K., Sonin G.V., Gusev A.V., Kuzina D.M., Sungatullina G.M. Breaking of the meteor particles in the atmosphere of the Earth and creation of magnetic microspheres, Meteoritic and Planetary Science 2018; 53: 6296-6296.
15. Popkiewicz M., Kardaś A., Malinowski Sz. Nauka o klimacie (Eng. Climate science). Wydawnictwo Sonia Draga, Warsaw, 2018.
16. Čapek D., Koten P., Borovička J., Vojáček V., Spurný P., Štork R. Small iron meteoroids-observation and modeling of meteor light curves. Astronomy and Astrophysics 2019; 625: A106.