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Meteorite impacts on Mars

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Abstract

The consequences of impact of a meteorite (less than 10 kg in mass) on Mars surface are investigated. The atmospheric braking is found to be important only for smaller objects with a strong dependence on density, impact angle and velocity of the meteorite. The limits for efficient atmospheric braking of incoming meteorites are determined, depending on initial mass, velocity and impact angle, but also on the surface atmospheric pressure at the moment of impact.

Keywords: Mars, meteorite flight, atmosphere stopping power

1. Introduction

Mars is in the research focus in the last decade. Several probes are currently in orbit and on the surface of the planet conducting various scientific missions with the common goal of gathering more data on Mars and its history. Space agencies are preparing for more advanced (possibly human) missions in the future. Most of the research is geological in nature, but other aspects of Martian environment are under consideration as well. In this context we tried to model meteorite impacts on the Martian surface and the ability (if any) of the Martian atmosphere to stop or slow down the impactors. Combined with knowledge of mean meteorite flux on Mars, the results obtained can be used to estimate the possible danger for robotic or human missions on the planet surface. To simplify the text we ignored the common astronomical terminology that makes distinction between a body in deep space, a body in the atmosphere and the one on the surface, and we simply used term meteorite for all these cases. Before we start our modelling, we need to know basic facts about the planet Mars, its atmosphere and the impacting bodies. Data we used in our modelling are summarized in the **Table 1** and **Table 2**.

Equatorial diameter (km)	6780
Surface gravity (m/s^2)	3.71
Atmosphere composition	96 % CO_2; 1.9 % Ar; 1.9 % N_2
Surface atmospheric pressure (Pa)	636
Expected variations of surface pressure (Pa)	400-870
Mean surface temperature (K)	210
Expected variations of surface temperature (K)	130-308
Mean orbital speed (km/s)	24
First cosmic speed (km/s)	3.57
Second cosmic speed (km/s)	5.03
Third cosmic speed (km/s)	34.1

Table 1: Physical characteristics of the planet Mars.

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The **Table 1** gives basic physical characteristics of the planet Mars, starting with its diameter and surface gravity. Note that, although Mars is about half the size of the Earth, its surface acceleration is only about one third of the surface acceleration of the Earth. Martian atmosphere is very rare; surface pressure varies widely depending on the location and the time of the Martian year. Mars is farther from Sun than Earth and is accordingly slower in its orbit. Also, the third cosmic velocity for Mars (the velocity needed for a body to leave the Solar System) is about three quarters of the corresponding velocity for Earth. Combined with a weaker Martian gravity, this results in lower impact velocities for Martian meteorites, compared to the Earth. Thus, meteorites will strike Mars with velocities between about 5 and 58 km/s, compared to 11 to 72 km/s for Earth.

The **Table 2** summarizes meteorite properties used in our calculations. In addition to common meteorite types found on Earth, we added ice as the lowest density meteorite group. Ice meteorites do not survive travel through the dense Earth's atmosphere so from the Earth's perspective, they simply do not exist. However, the Martian atmosphere is much less dense than the Earth's, and smaller incoming velocities increase the possibility of icy bodies reaching the planet's surface. The percent abundances of various meteorite types are taken from the fall statistics, i.e. the number of meteorites of a certain type found on the Earth. With no accurate statistics for Mars, we can only assume that the abundances are similar, with the argument that the origin of meteorites in both cases is the same, i.e. mostly the asteroid belt. Ice cannot survive the interplanetary environment unprotected so we can also conclude that ice meteorites will be rare, if any (larger chunks with surfaces covered by dust particles).

Meteorite types	Ice ? Chondrites 95 % Iron 5 %
Meteorite densities (kg/m^3)	Ice 917 Chondrites 3300 Iron 8000
Meteorite mass (kg)	0.001 - 28
Meteorite impact angle (towards horizontal, deg)	10 – 90
Meteorite incoming velocity (km/s)	10 - 50

Table 2: Physical characteristics of meteorites as used in our calculations.

2. Methods

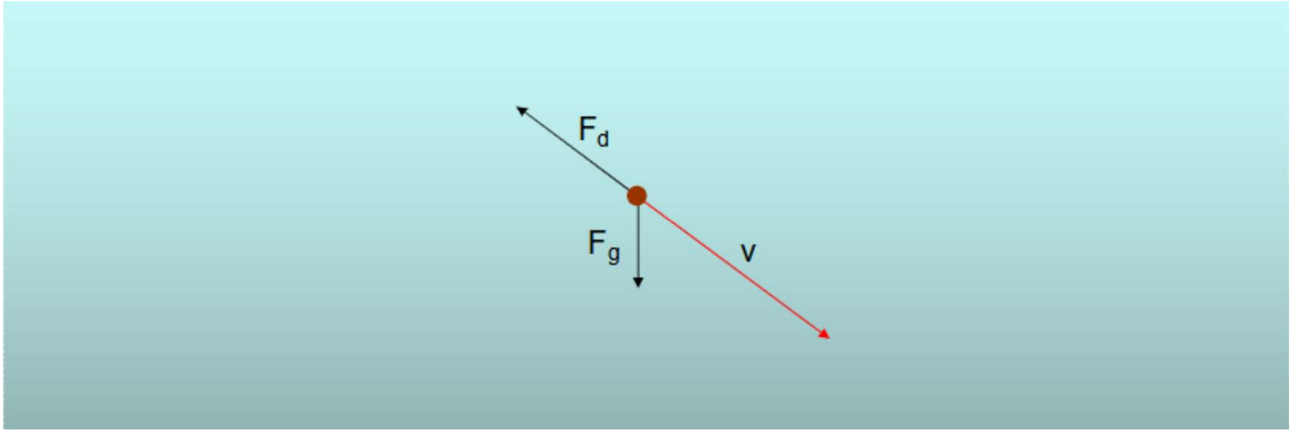

Figure 1: Forces acting on an incoming body in a planetary atmosphere. The incoming body is travelling with the velocity v, which is usually specified by its magnitude and the angle between the direction of the flight and the horizontal. The body is attracted towards the surface by the gravitational force F_g and is slowed down by the drag force F_d, which is always in opposite direction to the velocity.

The trajectory of the incoming body is determined by the forces acting on it. In this case the dominant force is the gravitational force of the planet Mars which, to a very good approximation, can be described by the Newton's **Equation** 1:

$$\overrightarrow{F_g} = G\frac{Mm}{r^2}\frac{\vec{r}}{r} \quad (1)$$

Where:
$\overrightarrow{F_g}$ is the gravitational force,
G is the universal gravitational constant,
M is the mass of the planet,
m is the mass of the incoming body,
$\vec{r}$ is the distance between centres of these two bodies.

It is common to rewrite this formula using the surface acceleration $\overrightarrow{a_g}$ as (**Equation 2**):

$$\overrightarrow{F_g} = \overrightarrow{a_g}m\frac{r^2}{r_o^2} \quad (2)$$

Where are:
$\overrightarrow{a_g}$ standing for surface gravitational acceleration,
r as before for the distance between the two bodies and
r_o the diameter of the planet.

The formula is valid for $r>r_o$. For small heights above the surface, the weakening of the gravitational acceleration with height is usually neglected, thus simplifying **Equation 2** to **Equation 3**:

$$\overrightarrow{F_g} = \overrightarrow{a_g}m \quad (3)$$

When the impactor enters the Martian atmosphere the drag force arises and Newton's drag law is used to describe it (**Equation 4**):

$$\overrightarrow{F_d} = -\frac{1}{2} c\rho A v^2 \frac{\vec{v}}{v} \tag{4}$$

Which simplifies to **Equation 5**:

$$\overrightarrow{F_d} = -\frac{1}{2} c\rho A v \vec{v} \tag{5}$$

Where:
c is the drag coefficient,
ρ is the density of the surrounding medium (Martian atmosphere in this case),
A is the cross-sectional area of the meteorite and
$\vec{v}$ is the relative velocity between the atmosphere and the meteorite.

The constant c depends on the meteorite shape and varies with the speed to a certain extent. For its values we used data from (**Carter at al., 2009**) for a spherical meteorite. As we are not interested in the exact location of the meteorite fall, we neglected wind in our calculations (in other case, wind would be included in the relative velocity term $\vec{v}$ in the drag equation). Similar argument applies to the planetary rotation which we also did not take into account.

In such a simplified situation, the model can be reduced to a two dimensional case by performing calculations in the plane of the meteorite trajectory. Here, x axis is horizontal, +x pointing in the direction of the flight, and y axis is vertical, pointing up. In this coordinate system the equation of motion of the meteorite can be written as **Equation 6**:

$$m\vec{a} = m\overrightarrow{a_g} - \frac{1}{2} c\rho A v \vec{v} \tag{6}$$

or, by the components (**Equations 7** and **8**):

$$a_x = -\frac{c\rho A}{2m} v v_x \tag{7}$$

$$a_y = -g - \frac{c\rho A}{2m} v v_y \tag{8}$$

These two equations are then solved numerically, starting with a meteorite at a large distance from the planet and ending with the collision with the surface.

3. Results

The parameter most interesting to us in this study is the ability of the Martian atmosphere to slow down the incoming meteorite. For this, we required, somewhat arbitrarily, that the meteorite should be slowed down by the atmosphere to below 1 km/s before it hits the ground. Although this is quite a large remaining velocity, it is much smaller than the initial meteorite velocity, so such a projectile would be much easier to slow down with some protective measure (shielding or sim.) than the meteorite with its initial velocity. We found that the dependence of the maximal mass of a meteorite that can be slowed down to our criterium is strongly dependent on the impact angle and the initial velocity. The results of our model for the most common stony meteorites passing through a "standard" Martian atmosphere are shown on the **Figure 2**.

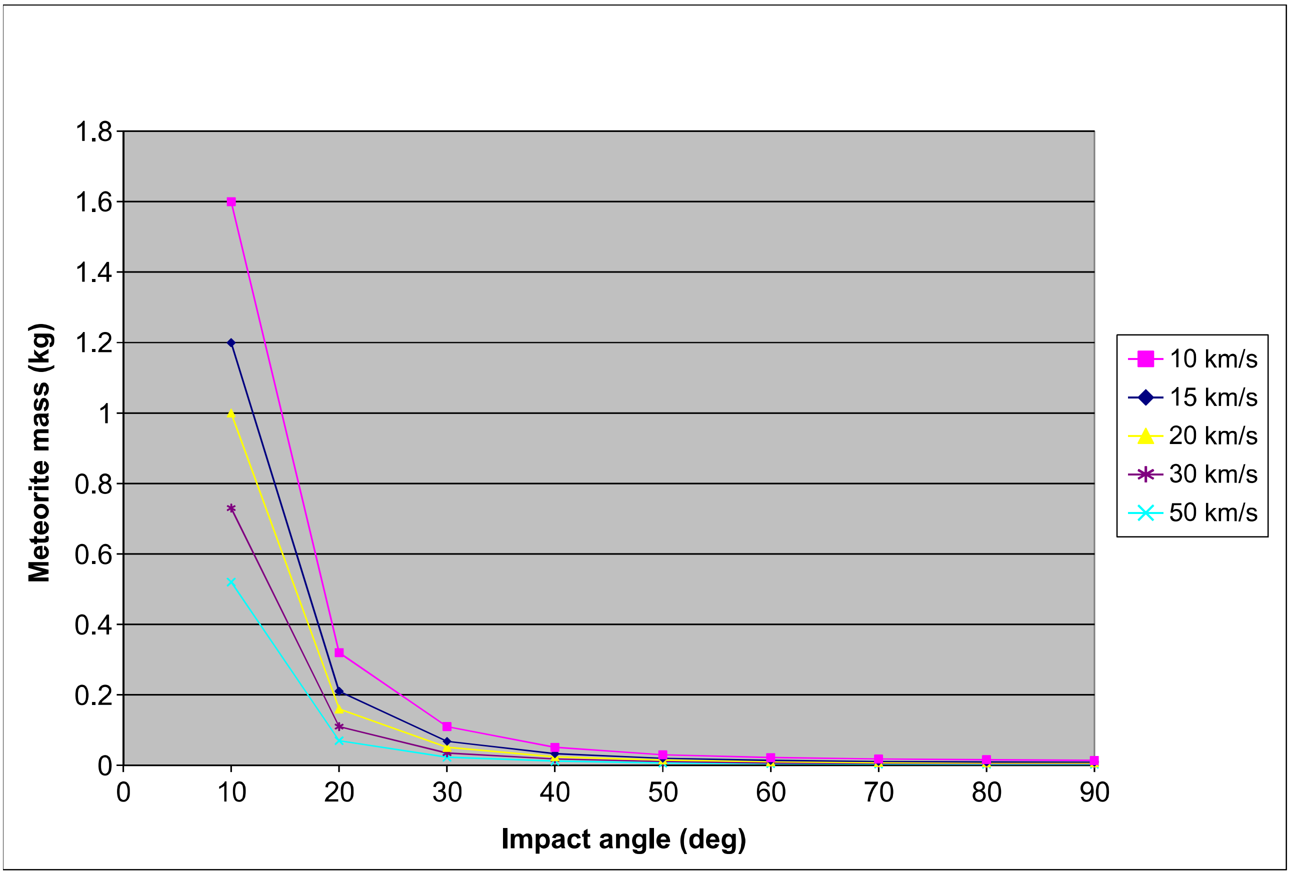

Figure 2: The dependence of the maximal mass of a meteorite that will be slowed down to 1 km/s before impacting the surface on the impact angle for various initial velocities. The graph is produced for the most common stony meteorite passing through a "standard" Martian atmosphere with a surface pressure of 636 Pa.

From the **Figure 2** it is obvious that the stopping power of the Martian atmosphere is extremely week indeed. The masses of meteorites that can be slowed down below 1 km/s are very small for all impact angles except the angles close to the horizontal. That means that any objects on the Martian surface (including people in protective suits) would be exposed to a large part of the incoming meteorite flux without any significant protection by the atmosphere. Moreover, the stopping power is strongly dependent on the surface atmospheric density at the moment of impact, as is illustrated by the **Figure 3.** At elevated places that naturally have lower surface pressure the protection by the atmosphere is minimal.

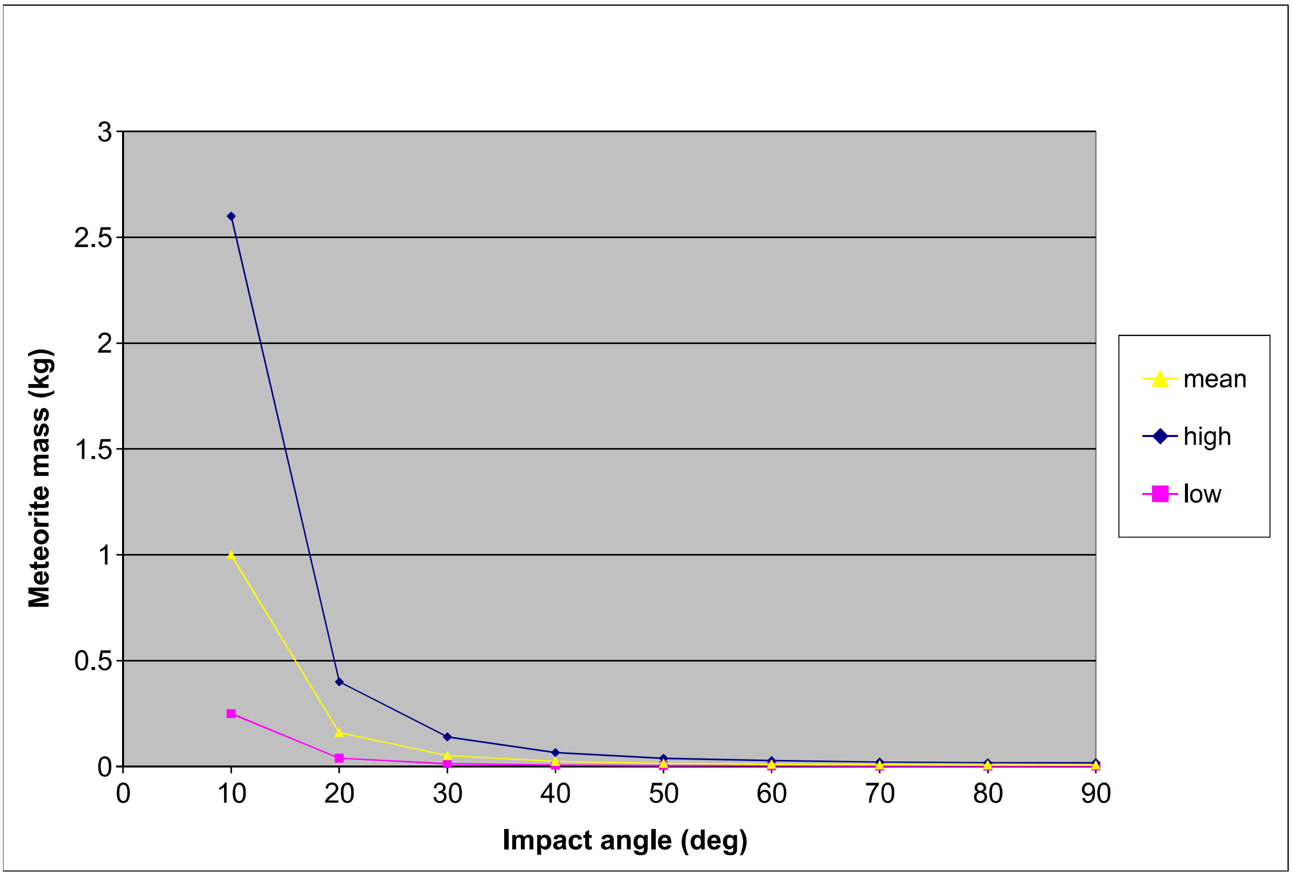

Figure 3: The dependence of the maximal mass of a meteorite that will be slowed down to 1 km/s before the impact on the impact angle for various atmospheric pressures. "mean" is the average pressure of the Martian atmosphere (636 Pa), "high" is the maximal expected pressure of 870 Pa and "low" is the minimal expected pressure of 400 Pa. The graph is produced for a stony meteorite with an initial velocity of 20 km/s.

The density of the meteorite (i.e., the material and consistence of the meteorite body) has a large influence on the ability of the Martian atmosphere to slow it down. Less dense meteorites have larger cross-section than more dense meteorites with the same mass and thus are exposed to a larger drag force. This fact is illustrated in the **Figure 4**.

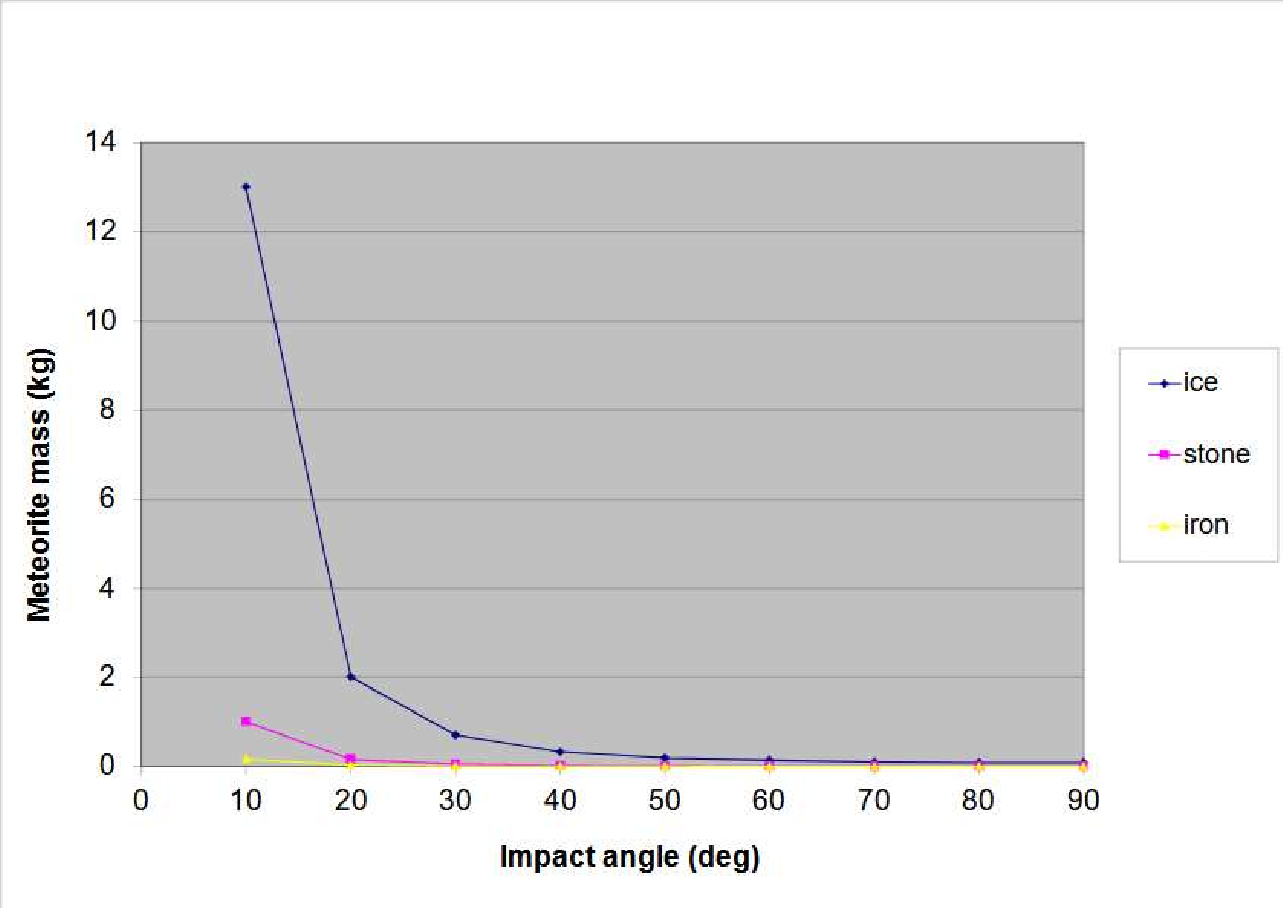

Figure 4: The dependence of the maximal mass of a meteorite that will be slowed down to 1 km/s before the impact on the impact angle, for three meteorite types (densities). The graph is produced for a meteorite with an initial velocity of 20 km/s

4. Discussion

The results show that the limiting size (defined as the maximal mass of the meteorite that will be slowed down to 1 km/s or less before the impact) strongly depends on four parameters: the incoming velocity, the incoming angle, the density of the meteorite and the surface atmospheric density at the time and place of the impact. In such circumstances it is hard to define a single "limiting" size of a meteorite that will be slowed down enough, but we can resort to taking the most unfavourable conditions. In such a case, the maximal mass of a meteorite that can be slowed down below 1 km/s is about 1g for the most common stony meteorites, about 50g for icy ones and less than 100 mg for the iron ones.

Some information about Martian meteor showers can be found in (**Jenniskens, 2006**) but estimated shower fluxes are missing. The average flux of the meteorites larger than these limits is about 10^{-14} $m^{-2}s^{-1}$ (**Grün et all, 2002**) at the Earth's orbit, and only slightly less at the orbit of Mars. The meaning of this is that any square meter of the Martian surface will be hit by a meteorite larger than the limit size once in 10^{14} seconds (about 3 million years). Thus our concern for the safety of unprotected objects/people on the Martian surface seems to be exaggerated. However, due to many simplifications made in this short study, further work is necessary to support this conclusion.

5. Conclusions

The results of the modelling of meteorite flight through the Martian atmosphere show that only small meteorites will be significantly slowed down. This is a consequence of the low density of the Martian atmosphere. Thus, for stony meteorites which are the most common type with the abundance of about 95 %, the limiting mass is about 1 g, for ice about 50 g and for iron less than 100 mg. A strong dependence on the local atmospheric density is shown. Also noticed is a less pronounced dependence on the impact parameters (impact angle and velocity). A rough estimate of the meteorite impact rate per square meter of Martian surface is one hit in 3 million years.

6. References

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Sažetak

Udari meteorita u Mars

Istraživane su posljedice udara meteorita (s manje od 10 kg mase) o Marsovu površinu. Atmosfersko usporavanje bitno je samo za manje meteorite uz snažnu ovisnost o gustoći, upadnom kutu i brzini meteorita. Određene su granice efikasnog atmosferskog usporavanja u ovisnosti o početnoj masi, brzini i upadnom kutu, ali i o površinskom atmosferskom tlaku u trenutku udara.

Ključne riječi: Mars, Let meteorita, Atmosfersko usporavanje

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Author's contributions

Ž.A. made the numerical flight model and carried out the calculations, I.S. analysed the results and prepared graphs.