Characterization of fireballs. Applications to detections of the FRIPON-MOROI network

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Terminology (Silber et al., 2018)

- *Meteoroids* are objects of asteroidal or cometary origin that have smaller size than asteroids that orbit the Sun
- The *meteor* is the luminous phenomenon generated by a meteoroid entering the atmosphere
- After the luminous phenomenon ends the object passes through the atmosphere; this part of the trajectory is called **dark-flight**
- The *meteorite* is the remnant matter that reaches the ground

Trajectory of a meteoroid entering Earth's atmosphere



Figure 1. Different stages of meteoroid atmospheric trajectory

Importance of study of meteoroids:

Meteoroids have preserved the same composition since the time of the formation of the solar system.

The study of meteorites provides information regarding the chemical composition from which the planets formed.

Our research is based on determing the ballistic coefficient α and the mass-loss parameter β for a selected sample of fireball events with noticeable deceleration ($V_f/V_0 < 0.8$).

Based on this analysis the events are classified in three categories:

(1) meteoroids that are likely to produce meteorites;

(2) meteoroids that can possibly produce meteorites;

(3) meteoroids that are unlikely to produce meteorites.

Introduction

The Fireball Recovery and Inter Planetary Observation Network (FRIPON) project was started in 2016 by IMCCE, Observatoire de Paris.

Purpose of the FRIPON project:

- to detect the meteors with the use of all-sky cameras,
- to determine their atmospheric trajectory,
- to and compute the strewn field.

In 2021 January the Meteorite Orbits Reconstruction by Optical Imaging (MOROI) project was integrated in FRIPON.



Figure 2. FRIPON camera installed on top of the Astronomical Institute of the Romanian Academy Bucharest. The camera has fish-eye lens with the focal length of 1.25 mm and the detector Sony ICX445.



Figure 3. FRIPON cameras installed in Europe Source: https://www.fripon.org/

Methods - The α - β algorithm (Gritsevich, 2008), (Gritsevich et al., 2012), (Sansom et al., 2019)

Equations of motion (Gritsevich et al., 2007):

$$M \frac{dV}{dt} = -\frac{1}{2} c_d \rho_a V^2 S, \qquad (1)$$

$$\frac{dh}{dt} = -V sin\gamma, \qquad (2)$$

$$H^* \frac{dM}{dt} = -\frac{1}{2} c_h \rho_a V^3 S. \qquad (3)$$

M is the mass of the meteoroid,*V* is the velocity of the meteoroid,

 γ is the slope of the trajectory,

S is the cross-section area,

h is the height above the Earth surface of the object,

 ρ_a is the density of the atmosphere,

 H^* is the effective destruction enthalpy, c_h is the dimensionless coefficient of heat transfer, c_d is the drag coefficient The following transformations are made (Gritsevich, 2007):

$$m = M/M_e, \quad (4)$$

$$v = V/V_e, \quad (5)$$

$$y = h/h_0, \quad (6)$$

$$s = S/S_e, \quad (7)$$

$$\rho = \rho_a/\rho_0. \quad (8)$$

where:

 M_e is the mass of the meteoroid prior to the entry in the atmosphere,

 V_e is the velocity of the meteoroid at the entry in the atmosphere,

 h_0 represents the height of the homogeneous atmosphere (7160 m),

 S_e is the cross-section area of the meteoroid at the moment of entry in the atmosphere,

 ρ_0 is the density of air near the surface of the Earth.

The following equations are obtained (Gritsevich, 2007):

$$m\frac{dv}{dy} = \frac{1}{2}c_d \frac{\rho_0 h_0 S_e}{M_e} \frac{\rho v s}{sin\gamma}, \qquad (9)$$
$$\frac{dm}{dy} = \frac{1}{2}c_h \frac{\rho_0 h_0 S_e}{M_e} \frac{V_e^2}{H^*} \frac{\rho v^2 s}{sin\gamma}. \qquad (10)$$

Assumptions:

$$s = m^{\mu}$$
$$\rho = \exp(-y)$$

(isothermal atmosphere) Initial conditions:

$$y = \infty, v = 1, m = 1$$

Equations (9)-(10) have the solution (Gritsevich, 2007):
$$m(v) = \exp(-\beta \frac{1-v^2}{1-\mu}) \quad (11)$$
$$y(v) = \ln 2\alpha + \beta - \ln(\overline{Ei}(\beta) - \overline{Ei}(\beta v^2)) \quad (12)$$

where:

$$\overline{Ei}(x) = \int_{-\infty}^{x} \frac{e^{z} dz}{z}$$

is the exponential-integral function

$$\alpha = \frac{c_d \rho_0 h_0 S_e}{2M_e sin\gamma} \quad (13)$$

is the ballistic coefficient and

$$\beta = \frac{(1-\mu)c_h V_e^2}{2c_d H^*} \quad (14)$$

is the mass-loss parameter.

The α and β parameters are the ones that minimize the expression (Gritsevich 2008):

$$Q_4(\alpha,\beta) = \sum_{i=1}^n (2\alpha \exp(-y_i) - \Delta_i \exp(-\beta))^2, \quad (15)$$

where

$$\Delta_i = \overline{Ei}(\beta) - \overline{Ei}(\beta v_i^2).$$

Results. FRIPON study sample

In 2021 the MOROI Romanian all-sky cameras network (Nedelcu et al. 2018) was integrated in FRIPON (Jeanne et al. 2019;Colas et al. 2020).

We focus on events with noticeable deceleration ($V_f/V_0 < 0.8$)

Time period analyses: January 2021 – March 2023

The study is based on applying the α - β algorithm (Gritsevich 2008) to the FRIPON detections in order to determine the final outcome for the meteoroid, the initial mass, and the final mass of the meteoroid, respectively.



Figure 4. Number of weekly detections made by FRIPON in Romania during 2021–2023. The high number of meteors in August is due to the Perseid meteor shower.



Figure 5. Sky distribution of detected meteoroids radiant.

Identification of meteorite producing fireballs

• Mass of the meteoroid at the entry in the atmosphere (Gritsevich 2008):

$$M_e = \left(\frac{1}{2}c_d \ \frac{\rho_0 h_0}{\alpha \sin \gamma} \frac{A_e}{\rho_m^{2/3}}\right)^3, \ (16)$$

where $A_e = \frac{S_e}{W_e^{2/3}}$ is the shape factor and W_e is the volume of the meteoroid,

 $\rho_0 = 1.29 \ kg \ m^{-3}$ is the density of air near the Earth's surface $h_0 = 7160 \ m$ is the height of the homogeneous atmosphere

The final mass of the meteoroid:

$$M_{f} = M_{e} \exp\left\{-\frac{\beta}{1-\mu} \left[1 - \left(\frac{V_{f}}{V_{e}}\right)^{2}\right]\right\}, (17)$$

where V_f is the velocity of the meteoroid at the end of the luminous trajectory

We consider
$$\left(\frac{V_f}{V_0}\right)^2 \to 0$$

Thus (Sansom et al. 2019):
 $M_f = M_e \exp\left\{-\frac{\beta}{1-\mu}\right\}.$ (18)

We introduce M_e^* like in Sansom et al. (2019):

$$M_{e}^{*} = \left(\frac{1}{2} \frac{c_{d} \rho_{0} h_{0} A_{e}}{\rho_{m}^{2/3}}\right)^{3} \quad (19)$$

So that

$$M_e = \frac{1}{\alpha^3 \sin^3 \gamma} M_e^*.$$
 (20)

Thus (Sansom et al. (2019)):

$$M_f = \frac{1}{\alpha^3 \sin^3 \gamma} M_e^* \exp\left\{-\frac{\beta}{1-\mu}\right\}.$$
 (21)

The mass-loss parameter β can be written as a function of ballistic coefficient α (Sansom et al. 2019):

$$\beta = (\mu - 1) \left[\ln \left(\frac{M_f}{M_e^*} \right) + 3 \ln(\alpha \sin \gamma) \right] \quad (22)$$

Thus, the boundaries that separate the domain in three regions ("likely fall", "possible fall", and "unlikely fall") are:

$$\mu = 0, \ln \beta = \ln \left[-\ln \left(\frac{M_f}{M_e^*} \right) - 3 \ln(\alpha \sin \gamma) \right] \quad (23)$$

and

$$\mu = \frac{2}{3}, \ln \beta = \ln \left[-\frac{1}{3} \ln \left(\frac{M_f}{M_e^*} \right) - \ln(\alpha \sin \gamma) \right]. \quad (24)$$

Let M_1 the mass of meteoroids having a spherical shape. In order to compute M_1 we take $A_e = 1.21$, $c_d = 1.0$ and $\rho_m = 3500 \ kg \ m^{-3}$ (Gritsevich 2008).

Let M_2 the mass of a meteoroid having a parallelepiped shape with the lengths 2L, 3L, and 5L (Gritsevich 2008). The shape factor becomes $A_e = 1.55$.

Table1. Mass of meteoroids

Event	$M_1(g)$ entry	M_1 (g) final	M_2 (g) entry	M_2 (g) final
20210107T182410	11.2	0	23.5	0
20210303T035840	188.0	0.3	395.3	0.7
20210327T232051	0.6	0	1.3	0
20210525T190753	1.1	0	2.3	0
20210713T192932	36.4	4.3	76.6	9.2
20210903T193410	8.8	0	18.5	0
20210904T202357	1.11	1.0	23.4	2.3
20210910T184600	545.1	0	1146.0	0
20210926T210704	181.9	1.3	382.4	2.9
20211024T192057	219.9	48.8	462.2	102.7
20220130T155708	731.0	0	1536.6	0
20220310T223953	15.8	0.1	33.2	0.3
20220321T224005	48.5	16.5	102.0	34.7
20220325T223826	1083.4	21.3	2277.3	44.7
20220329T221413	533.3	38.4	1121.0	80.9
20220803T210525	2946.9	0	6194.5	0
20221018T220501	1.99	0	4.2	0
20221113T155704	59.49	27.2	125.0	57.2
20230208T191245	99.9	45.0	210.1	94.7

Distribution of the α and β Parameters for Selected Fireballs



Figure 6

Distribution of the α and β parameters. The α and β parameters for the Cavezzo meteorite are computed from Gardiol et al. (2021). The α and β values for the Tunguska, Sikhote-Alin, Neuschwanstein, Benešov, Innisfree, and Lost City meteorites are mentioned in Gritsevich et al. (2012). The values for the other important detections can be found in: Devillepoix et al. (2018) (for Dingle Dell), Sansom et al. (2020) (for Murrili), Shober et al. (2022) (for Arpu Kuilpu), Devillepoix et al. (2022) (for Madura Cave), and Gritsevich et al. (2017) (for Košice). Case 1—Outcome for meteoroids with a spherical shape

• We consider the case $M_f = 50$ g, $c_d = 1.0$, $\rho_m = 3500 \ kg \ m^{-3}$, $A_e = 1.21$, and we obtain $ln\left(\frac{M_f}{M_e^*}\right) = -12.55$

and the boundaries:

$$\mu = 0, \ln \beta = \ln\{12.55 - 3\ln(\alpha \sin \gamma)\}$$
(25)
$$\mu = \frac{2}{3}, \ln \beta = \ln\{4.18 - \ln(\alpha \sin \gamma)\}$$
(26)

We consider the case $M_f = 25 \text{ g}$, $c_d = 1.0$, $\rho_m = 3500 \text{ } kg \text{ } m^{-3}$, $A_e = 1.21$, and we obtain $ln\left(\frac{M_f}{M_e^*}\right) = -13.25$ and the boundaries: $\mu = 0, \ln \beta = \ln\{13.25 - 3\ln(\alpha \sin \gamma)\}$ (27) $\mu = \frac{2}{3}, \ln \beta = \ln\{4.41 - \ln(\alpha \sin \gamma)\}$ (28)



Figure 7. Outcome for selected FRIPON detections.

The boundaries for different minimum terminal mass assumptions are shown. The input parameters are: $c_d = 1.0$, $A_e = 1.21$, $\rho_m = 3500 \ kg \ m^{-3}$. Case 2—Outcome for meteoroids a shape factor $A_e = 1.55$

We consider the case $M_f = 50$ g, $c_d = 1.0$, $\rho_m = 3500 \ kg \ m^{-3}$, $A_e = 1.55$, and we obtain $ln\left(\frac{M_f}{M_{*}^*}\right) = -13.30$ and the boundaries: $\mu = 0, \ln \beta = \ln\{13.30 - 3\ln(\alpha \sin \gamma)\}$ (29) $\mu = \frac{2}{3}, \ln \beta = \ln\{4.43 - \ln(\alpha \sin \gamma)\}$ (30) We consider the case $M_f=25$ g, $c_d=1.0$, $\rho_m=3500~kg~m^{-3}$, $A_e=1.55$, and we obtain $ln\left(\frac{M_f}{M_*^*}\right) = -13.99$ and the boundaries: $\mu = 0, \ln \beta = \ln\{13.99 - 3\ln(\alpha \sin \gamma)\}$ (31) $\mu = \frac{2}{2}, \ln \beta = \ln\{4.66 - \ln(\alpha \sin \gamma)\}$ (32)



Figure 8. Outcome for selected FRIPON detections.

The boundaries for different minimum terminal mass assumptions are shown. The input parameters are: $c_d = 1.0$, $A_e = 1.55$, $\rho_m = 3500 \ kg \ m^{-3}$. Case 3—Outcome for meteoroids with a spherical shape

- The density values $\rho_m = 2700 \ kg \ m^{-3}$ and $\rho_m = 3500 \ kg \ m^{-3}$ are considered

• If
$$M_f = 50 \text{ g}$$
, $c_d = 1.0$, $\rho_m = 2700 \text{ kg m}^{-3}$, $A_e = 1.21$,
we obtain $ln\left(\frac{M_f}{M_e^*}\right) = -13.07$ and the boundaries:
 $\mu = 0$, $\ln \beta = \ln\{13.07 - 3\ln(\alpha \sin \gamma)\}$ (33)
 $\mu = \frac{2}{3}$, $\ln \beta = \ln\{4.35 - \ln(\alpha \sin \gamma)\}$ (34)



Figure 9. Outcome for selected FRIPON detections.

The boundaries for different minimum terminal mass assumptions are shown. The input parameters are: $c_d = 1.0$, $A_e = 1.21$, m = 50 g.

Meteorite Candidate—The Meteoroid Detected at 20211024T192057



Figure 10. Meteoroid detected 20211024T192057 by stations Feleacu (ROCJ01) and Baia Mare (ROMM01).



Figure 11. The velocity during luminous phenomenon computed by FRIPON using a linear approximation on groups of five points for the fireball detected at 20211024T192057.



Figure 12. The altitude during luminous phenomenon of the event detected at 20211024T192057.



Figure 13. Normalized velocity (V/V_0) and height for the meteor detected at 20211024T192057.



Figure 14. Projection of luminous trajectories on map. The final point of the luminous trajectory is marked with red.

New important detections

- The atmospheric entry of asteroid 2023X1 on 13 February 2023
- The asteroid had 1 m in diameter
- discovered by the GINOP KHK program (K88, in Piszkéstető, Hungary)
- confirmed by the Visnjan observatory (L01, in Tican, Croatia)
- Strewn field conputed by Peter Jenninskens (SETI USA), Denis Vida(UWO, Canada), Auriane Egal (UWO and Space for Life, Montreal) and Hadrien Devillepoix (DFN – Australia)
- 10 fragments recovered

Source: https://www.fripon.org/



Figure 15. Search team. Credit: FRIPON/Vigie-Ciel. Source: <u>https://www.fripon.org/</u>



Figure 16. Loïs Leblanc, the member of the team who Recovered the meteorite in the town of Saint-Pierre-le-Viger (SeineMaritime) Source: <u>https://www.fripon.org/</u>

Valentine's Day meteorite found by PRISMA

- Detected by 3 PRISMA cameras (Castellana Grotte, Tricase and Vasto)
- Prisma experts Albino Carbognani (INAF-OAS) and Dario Barghini (INAF-OATo) computed the strewn field (located north of Mateira)
- Gianfranco and Pino Losignore noticed the debris on the balcony of their parents' home
- 12 fragments with a total mass of 70 grams were recovered
- Source: https://www.fripon.org/





Figures 17 and 18. Recovered fragments Credits: PRISMA/INAF Source: <u>https://www.fripon.org/</u> The main steps of the algorithm used in this paper are:

- 1. Compute the velocity of the meteoroid during the luminous trajectory;
- 2. Compute the slope γ of the trajectory;
- 3. Determine the initial velocity of the meteoroid;
- 4. Normalize the velocity of the meteoroid to initial velocity, normalize the height of the meteoroid to the height of the homogeneous atmosphere (7160 m), and obtain Equations (9) and (10);
- 5. Compute α and β that minimize the expression in (15);
- 6. Find the solution (11)–(12) of Equations (9) and (10);
- 7. Plot the curves corresponding to the minimum and

maximum of the dimensionless parameter μ ($\mu = 0$ and $\mu = 2/3$, respectively) that separate the domain in three regions: "likely fall," "possible fall," and "unlikely fall."

Future work:

- apply the α - β algorithm to events without deceleration;
- Introduce into the code a build-in recalculation for the realistic atmospheric conditions after Lyytinen & Gritsevich (2016) and see how these could improve the results;
- calculate the dark-flight trajectory for events identified in the "likely fall" and "possible fall" regions with the algorithms presented in Vinnikov et al. (2016), Moilanen et al. (2021), and Boaca et al. (2021).
- apply the algorithm to detections of the FRIPON in other countries;

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