Analysis of modern observations of meteor showers based on PTM methods

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Abstract. The work is focused on the analysis of modern observations of meteoroids included in the data bank formed by both professional researchers and amateur astronomers. Based on the modern physical theory of meteoroids (PTM), a new method for analyzing measurements developed, which provides the accuracy comparable with the results of radar observations. Due to the fact that the accuracy of the new method for analyzing meteoroids observations has increased significantly, it became possible to process observations of the Perseid and Leonid showers over a period of 120 years. The use of PTM made it possible for the first time to explain the distribution of meteor echo signals observed at an altitude of 2 MHz, at which the upper part of this distribution refers to an altitude of 140 km. In the process of work, a database of orbital characteristics of meteoroids was created. A method has been developed for modeling the probability of hitting a certain area of a meteor particle with a mass greater than a certain specified value and determining the density of a meteor shower from radio observations as well as a new “tomography” method for calculating the density distribution of sporadic meteors in the sky using radar observations of meteors at the same station with a goniometer. The method allows calculating the density of a meteor shower on the celestial sphere with an angular resolution of 2°. The use of these methods served as a proof that the distribution density of meteoroid showers on the celestial sphere has two planes of symmetry: the first coincides with the plane of the ecliptic, passing through the poles of the Earth, the other one is perpendicular to the plane of the ecliptic.

1. Introduction

The purpose of the work is that the new method has been developed for the analysis of modern observations of meteor showers, providing accuracy as in radar observations.

The scientific novelty is that the use of the new method allowed for the first time to interpret the distribution of meteor echo signals at an altitude of 140 km with a frequency of 2 MHz. As result the digital base of orbital parameters of meteors was built.

Currently, when studying the parameters of small celestial bodies, the modern physical theory of meteoroids (PTM) is used [1]. As a result, the evolution of the orbits of two large meteor showers was studied – Geminids and Quadrantid, which were intensively observed. The probability of genetic connections between Quadrantid and comets 1860 I, Tuttle, Pons-Broocks, Stephan-Oterma, and Kosik-Peltier was investigated [2]. The orbits of the Bootid and Bielid meteor showers were also
investigated [3]. All these results for both showers refer only to stable periods. The orbital planes of
the parent comets of these showers (Swift, Tuttle and Tempel-Tuttle) do not exactly coincide with
the ecliptic plane. As a result, the orbit of the Perseids meteor shower was studied. A relationship was
found between the parameters of the shower’s orbit and the ejection of matter by comet 1862 III
Swift-Tuttle [4] and comet Grigg-Skjellerup. Grigg-Skjellerup is a periodic comet orbiting Jupiter. In
this regard, a close approach to it will lead to a change in the radiant of the shower, and if the ejection
from the comet’s nucleus continues, almost simultaneously from 2 to 3 meteor showers will be
observed, differing in declination by 10° and 20°, respectively. It has been established that the activity
of the Perseids shower [5] has increased by 4 times since its discovery, and the longitude of the Sun
corresponding to the maximum activity has not changed [6]. At the same time, it passes near the Earth
and is of great interest for researchers dealing with comets. In 1967, the distance between it and the
Earth was estimated at 0.003 au. However, Jupiter’s gravity could affect the comet’s orbit. The
Leonids meteor shower has been studied. It was predicted and well observed. The studies have shown
that the activity of the Leonids shower has not changed over this period, but the longitude of the Sun at
maximum activity has increased linearly, and this increase is 2.6° over 120 years. This is explained by
the fact that meteoroids moving in orbits with the same orbital elements have a uniform distribution of
the perihelion argument [7]. As a result, the evolution was simulated from the moment of the shower’s
formation to the study of gravitational and non-gravitational perturbations from the parent comet on
based on correlation analysis with the observed structure of this shower [8]. Thus, the application of
the PTM in meteoric astronomy is a relevant and new direction of the study of meteoroids.

2. Orbital characteristics database

Electronic databases of catalogues of meteor observations were systematized [9] (Table 1).

| №  | File Name (Workbook) | Source         | Number of Meteors |
|----|----------------------|----------------|------------------|
| 1  | MCR040812.xls        | Lund, IAU MDC | 2529             |
| 2  | SOVP040803.xls       | Lund, IAU MDC | 1111             |
| 3  | HARP040803.xls       | Lund, IAU MDC | 1245             |
| 4  | FIRB040812.xls       | Lund, IAU MDC | 554              |
| 5  | TVJ040803.xls        | Lund, IAU MDC | 531              |
| 6  | MSS040803.xls        | IMO            | 2917             |
| 7  | CHE040809.xls        | Publ.Al AcadSCzR | 841         |
| 8  | UF040811.xls         |                | 528              |
| 9  | SAA040812.xls        |                | 79               |
| 10 | HAR6165_040803.xls   | Lund, IAU MDC | 19327            |
| 11 | HAR6869_040803.xls   | Lund, IAU MDC | 19818            |
| 12 | ADE6869_040803.xls   | Lund, IAU MDC | 1521             |
| 13 | MOG040803.xls        | Lund, IAU MDC | 5328             |
| 14 | KHA040803.xls        | Lund, IAU MDC | 5317             |

Analysis of the catalogues in Table 1 gave the following results:
1) Lund Meteor Data Center (Lund, IAU MDC) files were used in the January 1988 version;
2) After a certain period of time, some files in the catalogues have been lost. There are some
inaccuracies in the remaining catalogues;
3) Missing files OBNINSK.txt and ADE6061.txt;
4) The Lund Meteor Data Center files do not include signs for $a$ and $Q$. Hyperbolic orbits are
determined for values $e > 1$. Obviously, in this case $a$ and $Q$ have negative values. For parabolic
orbits in the database of the Lund Meteor Data Center, \( e = 1.000, \ a = 999.999 \) au and \( Q = 999.99 \)
au;
5) The first sheet of the working file for each catalog contains original data from literary or
electronic sources;
6) The second worksheet (“Data”) of the electronic database contains orbital or geophysical data
for each meteor in a single format.
The database on meteor catalogues was saved on HDD media as well as on CDs in a single format
as shown above.

3. Modeling the probability of hitting a certain area by a meteoric particle with a mass greater
than a certain specified value
Let the spacecraft (SC) move along a trajectory in the plane of the ecliptic.
At a certain point in time, the spacecraft ecliptic coordinates are set:
3. Modeling the probability of hitting a certain area by a meteoric particle with a mass greater
than a certain specified value
Let the spacecraft (SC) move along a trajectory in the plane of the ecliptic.
At a certain point in time, the spacecraft ecliptic coordinates are set: \( r \) – distance from the Sun
(AU); longitude \( L \); latitude \( B \), as well as the magnitude of the velocity vector \( V \) (km/s) and its direction
\( L_v \) and \( B_v \); direction of the normal to the exposed area \( L_0 B_0 \). We also set the value of the minimum
mass, above which the parameters of the flux of meteoric bodies are calculated [10]. The calculation
algorithm is as follows:

1) The longitude \( L_A \) corresponding to the direction \( \epsilon = 0^\circ \) is determined as: \( L_A = L + 90^\circ \).
2) Given \( L_0, B_0 \) in the \( \epsilon, \psi \) coordinate system, the direction of the projection of the normal to the
unit area on the celestial sphere is determined as:

\[
\cos \epsilon_0 = \cos B_0 \cos (L_0 - L_A) \\
\cos \psi_0 = (\cos B_0 - \cos \epsilon_0 \cos (L_0 - L_A)) / (\sin \epsilon_0 \sin (L_0 - L_A)) \\
\sin \psi_0 = \sin B_0 / \sin \epsilon_0
\]
(1)

3) In the same coordinate system, the direction of the projection of the velocity vector onto the
celestial sphere \( \epsilon_v, \psi_v \) is determined as:

\[
\cos \epsilon_v = \cos B_v \cos (L_v - L_A) \\
\cos \psi_v = (\cos B_v - \cos \epsilon_v \cos (L_v - L_A)) / (\sin \epsilon_v \sin (L_v - L_A)) \\
\sin \psi_v = \sin B_v / \sin \epsilon_v
\]
(2)
The exposed area gets meteoric bodies from a hemisphere with a pole at the point with coordinates
\( \epsilon_0, \psi_0 \).

4) The maximum possible relative velocity of a meteoric body at a given heliocentric distance is
calculated as: \( W_0 = V_0 + 30 \sqrt{(2/\tau)} \).

5) The step for setting the relative speed is determined as: \( \Delta W = W_0 / 36 \). In particular, for the
Earth’s orbit the result of division is 2 km/s. The calculation of the integral of the shower is carried out
by organizing three cycles.

6) Take the value \( \tau = 5^0 \).

7) The value \( \eta = 0 \) is taken. The value of the function \( f(\tau, \eta) \) is determined

8) For the given values of \( f(\tau, \eta) \), the coordinates of the visible radiant are calculated in the
coordinate system \( \epsilon_0, \psi_0 \):

\[
\cos \epsilon' = \cos \tau \cos \epsilon_0 - \sin \tau \sin \epsilon_0 \cos \eta \\
\cos \psi' = (\cos \tau - \cos \epsilon' \cos \epsilon_0) / (\sin \epsilon' \sin \epsilon_0) \\
\sin \psi' = \sin \tau \sin \eta / \sin \epsilon'
\]
(3)

9) We set the value of the relative speed \( W = \Delta W / 2 \).

10) According to certain values of \( \epsilon', \psi' \) and \( W \), the angle between the vector of relative velocity
and the spacecraft velocity is found as:

\[
\sin \kappa = \cos \epsilon' \cos \epsilon_v + \sin \epsilon' \sin \epsilon_v \cos \psi' \\
(4)

11) Due to the fact that the spacecraft moves in the heliocentric coordinate system with a velocity
\( V_0 \), the heliocentric velocity of the meteoric body will be equal to:

\[
V^2 = W^2 + V_0^2 - 2 W V_0 \cos \kappa
\]
(5)
12) If the speed $V > 0 \sqrt{2/r}$, then go to the next value $\eta$.
13) Otherwise, the coordinates of the heliocentric radiant are found as:

$$
\cos \varepsilon = \cos \chi \cos \varepsilon_\nu + \sin \chi \sin \varepsilon \cos \beta \\
\cos \psi = (\cos \chi - \cos \varepsilon \cos \varepsilon_\nu) \sin \varepsilon \sin \varepsilon_\nu
$$

Here,

$$
\cos \beta = (\cos \varepsilon' - \cos \kappa \cos \varepsilon_\nu) / \sin \kappa / \sin \varepsilon_\nu \\
\cos \chi = \left(W^2 - V^2 - V_0^2\right) / (2 V V_0)
$$

$$
\sin \chi = \sin \kappa W / V.
$$

14) The cell number for entering the Table 1 for $P_\varepsilon (V)$ is determined. For this purpose, the value $N_\nu = V \sqrt{r / \nu} 2/21$ is determined.
15) $P(\varepsilon, \psi)$, the cell numbers are determined by these coordinates:

$$
N_\varepsilon = \frac{\varepsilon}{10}, N_\psi = \psi / 10.
$$

16) The tables are used to determine the values of the functions $P_\varepsilon (V)$ and $P(\varepsilon, \psi)$.
17) All factors of the integrand are determined.
18) The summation determines the integrand.
19) With a step $\Delta W$, the relative speed changes, and the cycle is carried out with $W$.
20) With a step of $10^\circ$, the coordinate $\eta$ changes, and the cycle is carried out with $\eta$. The range of $\eta$ variation: from $0^\circ$ to $360^\circ$.
21) With a step of $10^\circ$, the coordinate $\tau$ changes, and a cycle in $\tau$ is performed. The range of $\tau$ variation: from $0^\circ$ to $90^\circ$. When these limits are reached, the summation process ends.

In practice, in some cases, for a given area, it is required to determine not the flow of meteoric bodies with a mass above a given one, but the flow of meteoric bodies that create an effect above a certain specified value $A_0$. This quantity can be, for example, an impulse normal to the surface of the site $A = m W \cos \tau$, or a breakdown of the coating:

$$
A = m (W \cos \tau)^{2.486},
$$

or in general:

$$
A = F (m, W, t) \geq A_0.
$$

Let

$$
m \geq G (A_0, W, \tau)
$$

is a solution to inequality (10), then

$$
N = 4.8 \times 10^{-14} \varphi(r) \int \int H \int m^{-2.2} dm d\tau d\eta
$$

$$
dW = 4.8 \times 10^{-14} \Phi(r) \int \int \int H \int G (A_0, \tau, W)^{-1.2} d\tau d\eta dW.
$$

In the case when the exposed area is randomly oriented during the spacecraft flight along the trajectory (the spacecraft “rolls over”), the procedure for calculating integral (12) changes:

1) some average value of the function $f$ in the formula (1–4) is calculated and then removed from the integral sign;
2) a factor of 0.5 is put in front of the integral, since meteors from the hemisphere always fall on the site;
3) the factor $\cos \tau$ is removed from formula (1–4);
4) to simplify calculations, it is assumed that the normal to the site is always directed in the same direction as the spacecraft velocity vector;
5) integration over $t$ is performed from $0^\circ$ to $90^\circ$.

In order to calculate the probability $P$ of a meteoric particle with a mass greater than some given $m$ hitting a certain area, it is necessary to divide the spacecraft trajectory into sections, for each section calculate the flux value $N_i$, then calculate the probability by the formula:

$$
P = 1 - \exp \left( -S \sum N_i \right) \Delta t_i
$$
where $S$ is the area of the site ($\text{m}^2$); $\Delta t_i$ – time of spacecraft passing through the $i$-th section of the trajectory in seconds.

Formula (13) is valid for the Poisson stream of events. Sometimes there are deviations from Poisson’s law during experiments on the satellite. In this case, the probability $P$ becomes less than that calculated by formula (13). Violations of Poisson’s law near the Earth can be explained by the influence of grouping of meteors due to their destruction in the upper layers of the atmosphere at the moment when larger particles touch smaller ones. Therefore, on the trajectory of the spacecraft flight, to calculate the probability, one can use formula (13).

4. Conclusion

The main task of meteoric astronomy is to build a model for the distribution and evolution of meteoric matter in the Solar System [11]. As a distribution model, one can take either the distribution of the orbits of meteoric bodies in the Solar System, or the distribution of the flux density of meteoric bodies over the celestial sphere as a function of the coordinates of a point in the Solar System [12]. A necessary condition is the reduction of the distributions to one minimum mass of the meteoroid. In order to fulfill this condition, it is necessary to correctly take into account the physical and instrumental selection [13]. The first is the fact that the glow and ionization produced by a meteoric body in the process of its destruction in the Earth’s atmosphere depend on its velocity [14]. Different minimum recorded masses will correspond to the same threshold of sensitivity of the equipment for optical and radio observations of meteors with different velocities of meteoroids [15]. The reduction of the observed data to a single minimum recorded mass of the meteoroid in this case is the account of physical selection [16]. The height of the meteor track also depends on the speed, which, in turn, affects the amplitude of the radio signal reflected from the meteor track during radar observations [17]. How large this influence is depends on the parameters of the radar. Within the directional pattern of the antenna system, the sensitivity of the radar is different, just as the sensitivity of the optical system for observing meteors within the field of visibility is different [18]. In this case, the reduction to a single minimum recorded mass of the meteoroid is the account of the instrumental selection [19].

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