Physical characteristics of space invasion

B.E. Zhilyaev, A.P. Vidmachenko*, A.F. Steklov

The Main Astronomical Observatory of the NAS of Ukraine, 03143, Academician Zabolotny str., 27, Kyiv, Ukraine

This paper presents an example of the application of theoretical developments on some issues of physics of space invasion. The effect of brightness oscillations and “wobbling” in the meteor trail, which we discovered, allows us to obtain estimates of some characteristics of the meteor by measuring the frequency of changes in the brightness in the trace ($f_c$) and meteoroid oscillations ($f_m$), if its velocity and altitude are known. Based on the proposed “tuning technique”, it is possible to determine the characteristics of the meteor at one-sided observations. To do this, we set the initial parameters for the model of meteoroid dynamics by the coincidence of the calculated and measured values of the frequencies $f_c$ and $f_m$. Our simulation allows us to find the altitude at which the ratio of frequencies $f_c/f_m$ coincides with the value found in the explosion of a meteoroid. Using this “tuning technique” and assuming the mineral composition for the meteor, we found estimates of the initial velocity of 21 km/s and the mass of 850 kg of the meteoroid, which reached a critical value of surface speed at an altitude of about 20.9 km in about 7.9 s with a residual mass of about 13.9 kg and a residual speed of about 10.9 km/s. At that moment, the meteoroid exploded.

Keywords: space invasions, astronomical observations, photometry, meteors.

1. INTRODUCTION

The inspiring image was snapped by photographer Krista Trinder, which was 19/11/2020 honoured as NASA’s Astronomy Picture of the Day (Fig. 1). This photo depicts a landscape over Childs Lake, Canada, captured with long exposure [10]. Such celestial phenomenon known in scientific circles as the “Strong Thermal Emission Velocity Enhancement”, or “STEVE” for short, is seen shimmering over the horizon. This phenomena has been frustrating perplexed scientists at US-based space agency NASA for years. Such light was first confirmed five years ago, but experts remain puzzled as to its cause. The colourful streaks consist of a “purple ribbon in the sky, with a green picket fence structure underneath”, NASA said in an accompanying statement. The space agency added it as “aurora-like”, meaning it seems to resemble the natural electric phenomenon responsible for the world-famous Northern Lights.

![Field observation of the intrusion in Canada. The meteoroid inversion trace, which indicates its movement in the atmosphere of the Earth.](image1)

Fig. 1. Field observation of the intrusion in Canada. The meteoroid inversion trace, which indicates its movement in the atmosphere of the Earth.

We consider this image as a trace of a meteoroid that entered the atmosphere at an angle of 36 degrees and at a positional angle of 6 degrees. It follows from the image that the explosion occurred at the coordinate $X = 200$ and the pieces then fell apart.

2. THEORY

Fig. 3 shows the light curve of the centre of gravity of the inversion trace with the oscillation frequency of 1.66 Hz (drag frequency $f_\text{d}$) on a time scale of 7.9 seconds. The wobbling frequency of the centre of gravity

*Vidmachenko Anatoliy Petrovych; vida@mao.kiev.ua
Fig. 3. The light curve of the centre of gravity of the inversion trace of the inversion trace $f_m$ is estimated at 1.12 Hz.

It is well known that a swirling ball flies along a curved path. Deviations from rectilinear motion indicate the presence of strength perpendicular to the direction of the flight path. This phenomenon is known as the Magnus effect. It occurs when a stream of gas flows around a rotating body.

The equation of motion of a meteoroid of mass $m$ and velocity $v$ is written in the form:

$$m\ddot{v} = F_c + F_m,$$

where the aerodynamic drag force $F_c$ and the Magnus force $F_m$ acting on the meteoroid. The aerodynamic drag force $F_c$ is:

$$F_c = \frac{1}{2} C_D \rho \omega_s \pi r_m^2,$$

where $C_D$ is the drag coefficient depends on the shape of the body. The simplest expression for the Magnus lifting force $F_m$ is known for a cylindrical body [1]:

$$F_m = 2S \rho r_m \pi \omega_m \left| \mathbf{v} \times \mathbf{\omega}_m \right|,$$

where $S = \pi r_m L_m$ is an area of a cylinder, $r_m$ and $L_m$ are the radius and length of the cylinder, $\rho$ — gas density, $v$ — flow velocity at infinity, $\omega_m$ is the frequency of angular rotation.

In the linear approximation, we can neglect variations of $v$ within $H_\rho$ along the meteoroid track $z$, where $H_\rho$ is the height of the homogeneous atmosphere, approximately 7 km.

In this approximation the equation of motion of a meteoroid give the oscillation solutions [2].

The angular frequency of the brightness variations $\Omega_e$ has the form

$$\Omega_e = 2\pi f_e = \sqrt{\frac{3}{4} C_D \rho \omega_s^2 v^2},$$

where $\rho_m$ is the density of meteoroid.

The main frequency of rotation of Magnus $\Omega_m$ has the form

$$\Omega_m = 2\pi f_m = \frac{3}{2} \frac{\rho \omega_m}{\rho_m} \left( 1 + \frac{z}{H_\rho} \right).$$

A meteoroid can be considered as an air turbine that converts the energy of the airflow into rotational energy. We can obtain an estimate the angular frequency of the rotation of the meteoroid as [3]:

$$\omega_m = \sqrt{\frac{C_D \rho v^3 S T}{I}}.$$

Here $T$ is the time span, $I$ is the moment of inertia around the axis of rotation.

Most meteoroids end with an explosion. As the meteoroid moves the atmospheric density increases and the stagnation pressure at the meteoroid $p_s = \rho v^2$ rises, up to destruction value $p_s = Y$, where $Y$ is Young’s modulus. Destruction of a meteoroid occurs also when the centrifugal force arising from rotation becomes equal to the normal force determining the tensile strength of the material of which the meteor consists $Y = \rho_m \omega_m^2 r_m^2 = \rho_m v_m^2$, where $v_m$ — rotation speed on the meteoroid surface.

Laboratory studies have shown that the tensile strength $Y$ for different samples of stone meteorites varies in the range of 20 to 200 MPa [4]. Thus, the value of the velocity $v_m \approx 3$ km/s can be considered as a conditional value for meteoroid of mineral composition.
3. MODEL OF THE ABLATION FOR ESTIMATION THE METEOROID CHARACTERISTICS

Last time the computer program has been developed for estimating the environmental consequences of an asteroid impact on Earth. The program requires six inputs: impactor diameter, impactor density, impact velocity before atmospheric entry, impact angle, and the target type (sedimentary rock, crystalline rock) [7, 6]. The motion of a meteoroid through the atmosphere in 3D simulations was performed by set of authors [7, 8]. We use the classical meteor ablation theory [6, 9].

The model can be implemented by the Impact 4A Software [6]. The numerical integration of the differential equations was performed using the Runge–Kutta 4 integrator. This was found to be stable at time steps of 0.001 s. We construct a grid of intrusion models using the Impact 4A software program on the plane of the

![Graph](image)

**Fig. 4.** The speed of the meteoroid depending on the height, the speed of rotation on the surface and the critical speed of dynamic destruction

![Graph](image)

**Fig. 5.** The time span and the value of the meteoroid mass depending on the height

![Graph](image)

**Fig. 6.** The values of the frequencies $f_c$, $f_m$ depending on the height (left). The frequency ratio $f_c/f_m$ coincides with the value found from the measurements on the height of 20.9 km, on a time of 7.9 sec (right). At this moment a meteoroid exploded and destroyed.
primary “mass — speed” meteoroid. As a result of modelling, we find the height at which the frequency ratio \( f_c/f_m \) coincides with the value found from measurements for exploding meteoroid.

4. COMPARISON OF THEORY AND OBSERVATIONS

The ablation of an 850 kg solid meteoroid with an initial velocity of 21 km/s was simulated using the Impact 4A Software considered above [6].

Fig. 4 shows the speed of the meteoroid depending on the height, the speed of rotation on the surface and the critical speed of dynamic destruction. It is easy to see that the limit of dynamic fracture was reached.

The meteoroid reached a critical value of the stagnation pressure at an altitude of 20.9 km in a time of about 7.9 sec with a residual mass of 13.9 kg, and a residual speed of 10.9 km/s (Fig. 5). At this moment a meteoroid exploded and destroyed.

Fig. 6 plays a crucial role in our work. The figure shows the values of the frequencies \( f_c, f_m \) depending on the height. By varying the initial parameters of the model, the primary mass and speed of the meteoroid at the boundary of the Earth’s atmosphere, we find the height at which the frequency ratio \( f_c/f_m \) coincides with the value found from the measurements on time of 7.9 s.

5. METEOROID’S CHARACTERISTICS.

1. A parent object weighing 850 kg entered the atmosphere at a speed of 21 km/s.
2. Burned, lost mass, rotated, shone like Venus.
3. After about 8 seconds it exploded at an altitude of about 21 km. The residual mass of about 14 kg at a speed of 11 km/sec fell apart into several fragments, which continued to fall.

Thus, we show that “tuning technique” in combination with a simulation model of intrusion allows determining the meteor characteristics during one-side observations [11–16].

Физические характеристики космического вторжения
Жиляев Б.Ю., Видьмаченко А.П., Стеклов О.Ф.

Головная астрономическая обсерватория НАН Украины, 03143, г. Киев, ул. Академика Заболотного, 27

У этой работе представлен приклад использования теоретических разработок по некоторых вопросам физики космических вторжений. Влияние колебаний яркости и "качания" в метеорном следе, который мы обнаружили, позволяет получить оценки некоторых характеристик метеора, измеряя частоту изменения яркости в следе ($f_c$) и метеороида ($f_m$), если известны его скорость и высота. На основе предложенной "методики настройки" можно определить характеристики метеора при односторонних наблюдениях. Для этого зададим исходные параметры модели динамики метеороида по совпадению расчетных и измеренных значений частот $f_c$ и $f_m$. Наше моделирование позволяет нам найти высоту, на которой отношение частот $f_c/f_m$ совпадает со значением, найденным при взрыве метеороида. Используя эту "технику настройки" и предполагая минеральный состав метеора, мы получили оценки начальной скорости 21 км/с и массы 850 кг метеороида, которые достигли критического значения поверхностной скорости на высоте около 20,9 км примерно за 7,9 с при остаточной массе около 13,9 кг и остаточной скорости около 10,9 км/с. В этот момент метеороид взорвался.

Ключевые слова: космические вторжения, астрономические наблюдения, фотометрия, метеоры.