EPSC2018

SB16 abstracts

13 Sep 2018 15:37:37

EPSC Abstracts
Vol. 12, EPSC2018-88, 2018
European Planetary Science Congress 2018
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The fireball of 21/09/2017: A study of eyewitness reports

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Abstract

On September 21, 2017, a large fireball appeared over the Netherlands and vanished over the North Sea. Scores of eyewitness reports with descriptions of the phenomenon arrived through our notification e-mail address feuerkugel@dlr.de. By studying these reports, given with varying level of details, and by comparing them with other trusted sources we may appreciate how reliable and complete the reported data are. This might be helpful for us to improve our notification system in the future. Also, reports sometimes include information not easily obtained by other observing techniques. On the other hand, the reporting system is useful to promote public awareness of Earth in the environment of space.

1. Introduction

The Institute of Planetary Research of the German Aerospace Center (DLR) maintains the notification e-mail address feuerkugel@dlr.de ("Feuerkugel" meaning fireball in German). Eyewitnesses of fireball events are encouraged to send us an e-mail with information on time and place as well as a rough description of the event. The more detailed the report, the easier is the identification of possible double observations of the meteor in the image data from the European Fireball Network (EN) [1]. We receive up to two dozens of reports on sporadic meteors every month. The corresponding guide is in German, therefore reports are almost exclusively from German-speaking countries. Additionally, we often receive requests to identify potential meteorites.

2. Fireball of 21/09/2017

In the evening hours of September 21, 2017, a large fireball appeared over the Netherlands and vanished over the North Sea. We received an unusually high number of 79 witness reports from many parts of Germany. Most reports were sent from observers in the Rhine-Ruhr region close to the border to the Netherlands (Fig. 1). The reports varied greatly in quantity and quality of the given information. Locations from where reports were sent are highly biased by population density in the respective areas (note the reports from the heavily populated Rhine-Ruhr region) and local weather conditions. Also, many people enjoying outdoor activities at a still early night helped to increase the amount of potential eyewitnesses.

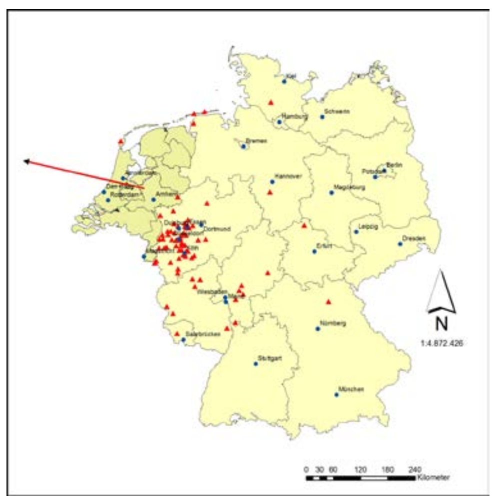

Fig. 1: Map of locations from where eyewitness reports from Germany and the Netherlands were received. The solid red line depicts the presumed location of the meteor given by [2].

3. Analysis

We have gathered the information given by the eyewitnesses and have analyzed the data in the following categories: time, duration, brightness, color, and flight direction.

Most reports put the fireball in a timeframe from 20:55 to 21:10 local time (CEST) (Fig. 2). Jörg Strunk's Mintron astro camera in Herford in North Rhine-Westphalia detected the fireball at 21:00:08 which agrees with the reports. EN station 40 in Kalldorf (North Rhine-Westphalia) also imaged the fireball, but due to the long exposure time the exact event time cannot be resolved.

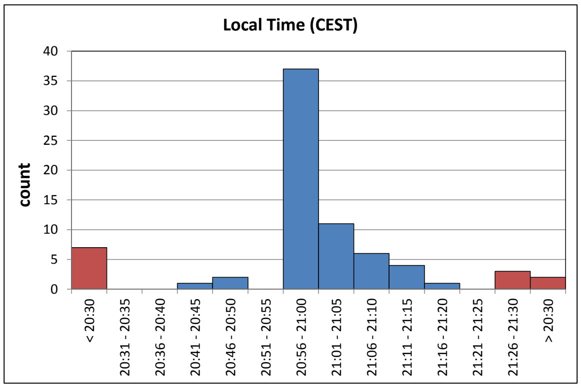

Fig. 2: Reported observation time (outliers in red).

The most mentioned colors were green/blue and white (Fig. 3). But other colors were also reported (red, orange, purple), possibly due to different flight phases of the meteor that had been observed by the individual witnesses.

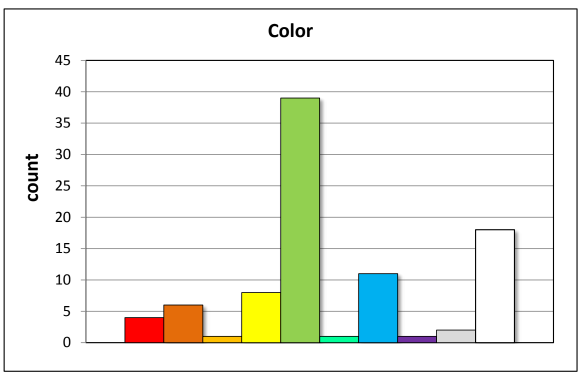

Fig. 3: Color reports.

Duration reports scatter a lot with a mean value of 3-4 seconds. An overwhelming majority reported a westward flight direction of the fireball (Fig. 4), which coincides with the analysis from [2]. The brightness has been described by comparing it to other bright light sources (planets, fireworks, flare guns etc.) or as just being "very bright".

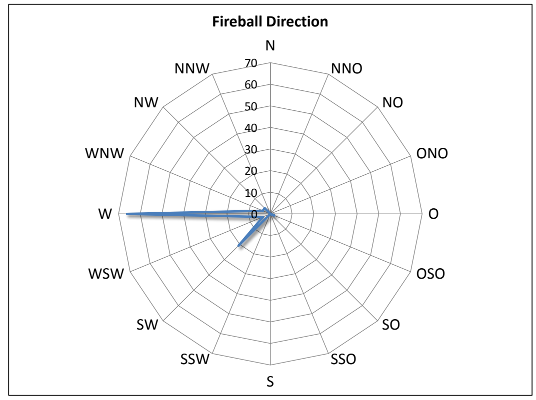

Fig. 4: Flight direction of the fireball.

4. Summary and Outlook

We have analyzed 79 eyewitness reports of a prominent fireball, observed on September 21, 2017. While the general flight direction was mainly described correctly, given information on color and duration of the event vary to a certain degree. An estimation of the meteor's magnitude from these reports alone is hardly possible. Also, the exact time of the event can only be determined with relatively low accuracy.

Later in 2017, another large fireball was reported by dozens of witnesses. We will analyze these reports and compare the results with the data from this work. In the future, these findings might help in overhauling the notification form to derive more reliable results from the witness reports.

We make attempts to respond to each observer report to address observers' questions and concerns. Such reporting system is useful to promote public excitement and awareness of Earth in space. We already noticed an increase of reports over the last years, maybe a result of our and our partner's ongoing public outreach work.

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EPSC Abstracts
Vol. 12, EPSC2018-271, 2018
European Planetary Science Congress 2018
ⓒ Author(s) 2018

Redox reactions in meteoroid atmospheric entry reproduced in plasma experiments

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Abstract

Atmospheric entry of meteoroids has been reproduced in a high enthalpy facility, with basalt as a meteorite analog and an ordinary chondrite, to investigate the redox reactions triggered by interaction between the newly formed melt and the atmospheric gases under high temperature. The resulting material has been analyzed by electron microprobe, LA-ICP-MS, and X-ray Adsorption Spectroscopy (the latter to determine the oxidation state of Fe). The observations on the experimentally produced melt perfectly match those from natural meteorite fusion crusts.

1. Introduction

Melting, evaporation, ablation, and redox variations occurring during the atmospheric entry of extraterrestrial material may affect microstructures of and induced chemical changes in the recovered meteorites and cosmic spherules, inducing a bias in our interpretation. This problem is generally approached by numerical modeling (e.g., [1]) or heating experiments, which however are far from reaching the conditions experienced by meteoroids (e.g., [2,3]). In the VKI Plasmatron, an induction-heated plasma wind tunnel creates a steady state plasma flow up to 2200 Pa pressure, 10,000 K temperature, and a potential heat flux of 16 MW/m^2. It operates with N_2, CO_2, and Ar as plasma gases, is commonly used for testing spacecraft heat shields and, therefore, represents a good approximation of the conditions encountered by any material during the atmospheric entry. Recently, a plasma tube has been used for similar experiments but with a different set-up [4]. Here we present the results of a series of experiments, testing different material and experimental conditions, which produced features that are very close to those observed in natural samples [5,6] and that shed light on the environmental conditions and the redox reactions occurring during the process.

2. Methods

Cylinders of ca. 1 cm diameter and 2 cm length were drilled from a specimen of a coarse-grained, alkali- and water-rich basalt, specifically selected to investigate volatilization of light elements, and used here as analog for meteorites, and from a sample of the H5 El Hamammi ordinary chondrite meteorite. Two types of sample holders, in cork and graphite, were used, as they have different thermal properties. Several experimental conditions have been tested (Table 1). The recovered material after the experiments has been embedded in epoxy, cut in two halves, and mechanically polished for detailed characterization. Preliminary analyses include micro-XRF and SEM, equipped with EDS detector, at the VUB, followed by EMPA at the NHM-Vienna, LA-ICP-MS at Ghent University (Belgium), and Fe K-edge X-ray Absorption Spectroscopy XANES and EXAFS at beamline BM08 of the ESRF storage ring in Grenoble (France) according to the method described in [7-9].

Table 1: Melting experiments

Exp no.	Sample holder	Heat flux (MW/m^2)	P (Pa)	Duration (s)
B 1.1	cork	3.04	1500	41
B 1.2	graph	3.12	1500	21
B 2.1	cork	1.01	20000	12
OC 2.1	cork	1.01	20000	21

3. Results

During the experiment, fragments of unmelted basalt were ejected and droplets of melt were observed to flow radially on the surface of the sample holder. The recovered quenched material exhibits a strong depletion in alkali and generally highly volatile elements, with an apparent enrichment in refractory elements. Spectroscopic analysis during the experiments shows that Na, K, Mg, and Ca, ordered for decreasing concentration, are ablated. On a second order, Fe and Ti are also volatilized. The surface temperature, measured with a pyrometer and calculated with the Planck curve, was ca. 2100-2300 K. Despite the rapid cooling to ambient temperature, evidence of devitrification is noted in all samples. The melt exhibits *schlieren* and flow fabric. Tiny vesicles are coated by iron oxides. Locally, melt spherules have formed, representing the experimental analog of meteoroid ablation spherules.

The resulting melt is clearly depleted in the alkali metals and significantly enriched in Ti and Mg (both refractory elements), but plotting the elements according to their volatility does not reveal any clear trends. The spherules are enriched in SiO_2 with respect to the original basalt. In experiments using a graphite sample holder, at the contact with the graphite some Fe-Si metal alloys have crystallized, and the material exhibits a further enrichment in Ni (20 times higher than the preserved basalt) and Cr. In both experiments, the melt appears to be enriched in the REE (normalized on CI) and in the moderately siderophile elements with respect to the preserved basalt. The XAS spectrum of the starting basalt displays values of the edge energy that are typical of trivalent Fe. As the starting material is a multiphase mixture, it is difficult to determine accurately the Fe oxidation state by means of the pre-edge peak centroid in the absence of constraints on the Fe content in the constituting phases. However, by comparison with values of Fe model compounds, $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ ratio is evaluated close to 0.75±0.15. The edge energy of the melt sample is consistent with the presence of Fe^{2+}. Pre-edge peak data allow an accurate evaluation of a $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ ratio close to 0.19±0.05.

The melt resulting from experiments on the ordinary chondrite presents widespread vesiculation and is internally largely crystallized. Similar to natural samples [5,6], the transition between the unaffected material and the melt is marked by fractures minerals and by trails of metal-rich inclusions along. The crystallized phase that dominates in the melt is olivine, sub-euhedral to skeletal, including hopper shape [10]. Locally, rounded olivine fragments are preserved, suggesting incipient melting. New olivine has overgrown on these fragments, exhibiting a progressive change in composition towards more Fe-rich terms, after an initial apparent enrichment in Mg, exactly as in natural samples [6]. Locally, new olivine is enriched in Ca, Cr, and Ni (the latter is almost absent in the original olivine), and depleted in Mn. In the groundmass, opaque phases crystallized, either skeletal (magnetite) or botryoidal (Fe, Ni, and related oxides). The melt is enriched in TiO, FeO, and Cr_2O_3, all relatively highly siderophile. The rare earth elements are also enriched in the melt with respect to the bulk meteorite.

4.Conclusions

The sample holder has a strong influence on the redox environment recorded by the final product. Interestingly, all experiments, independently from the used jacket, show enrichment of the melt in moderately siderophile elements, whose partitioning in the melt depends on the fO_2 [11]. The experiment with the ordinary chondrite has reproduced the same features observed in a natural meteorite fusion crust coating a similar type of meteorite. In summary, both XANES and microanalysis suggest possible reduction rather than oxidation of the quenched melt, but in a dynamic environment with complex redox reactions, leading to a non-unequivocal interpretation of the process.

Acknowledgements

G. Batic of the NHM for sample preparation, J. Roszjar and D. Topa for assistance with the EMPA at the NHM. We thank the Research Foundation Flanders (FWO) and the Austrian Science Fund (FWF, Project V505-N29) for support.

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EPSC Abstracts
Vol. 12, EPSC2018-277, 2018
European Planetary Science Congress 2018
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Simulating Atmospheric Alteration of Micrometeorites using a Two Stage Light Gas Gun.

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1. Introduction

An estimated 20-30,000 tonnes of extra-terrestrial dust arrives at the Earth each year [1] with up to 90% of this mass burning up during atmospheric entry [2]. These particles are largely thought to sample asteroids and comets. Analysis of those particles that survive atmospheric entry to arrive at the Earth's surface (micrometeorites, MMs) suggest they sample a larger number of parent bodies than meteorites. MMs therefore have the potential to provide us with a more complete picture of the contents of the Solar System. Many MMs have, however, experienced both morphological and chemical changes as a result of intense heating during atmospheric entry. These melted particles are referred to as cosmic spherules (CSs) and are amongst the most abundant source of extra-terrestrial matter on the Earth's surface [3]. Understanding the alteration processes which particles have experienced during atmospheric entry, such as melting and vaporization, will enable us to better understand the contribution these particles make to the Earth (both it's atmosphere and surface). It will also allow us to gain greater insight into the precursor MM's mineralogy, providing a better understanding of the parent bodies from which the particles originate. Previous experimental attempts to understand the heating effects of atmospheric entry on micrometeorites have subjected a variety of MM analogues to pulse heating [4,5]. In these experiments, the particles have been heated uniformly. Due to the non-symmetrical shape of many of the grains entering the Earth's atmosphere they will likely experience tumbling during entry, resulting in non-uniform heating and the differentiation of molten elements of different densities [6], both of which would not be replicated during such stationary heating. This may explain why magnetite rims and the loss of non-volatile materials (e.g. iron-nickel beads) are not observed in these experiments [5]. Some groups have also attempted to use computer simulations to model the ablation of atoms from heated particles [7]. These models have provided interesting results that suggest that cometary materials can survive entry through Earth's atmosphere, but largely rely on the use of theoretically rather than empirically derived parameters. Some groups are also investigating the possible use of Reddy Shock Tubes [8].

2. Method

Here we report the results of our attempts to use the two stage light gas gun (LGG) at the University of Kent to replicate the interactions of a MM analogue travelling at hypervelocity through an atmosphere. The LGG is capable of firing single solid projectiles up to 3 mm in diameter at velocities up to 7.5 km/s [9], however, during shots the gun and LGG's target chamber must be evacuated down to 0.5 mBar. We have therefore designed an environment chamber (Figure 1) to fit within the target chamber that is capable of containing a sealed atmosphere up to a pressure of 2 atm. The environment chamber consists of a Plexiglas tube, with a solid aluminum breech and uses an aluminised Mylar film to seal the front end. The projectile enters the chamber by penetrating the Mylar foil and travels through the atmosphere before being captured by an aerogel block. The effects of aerogel on hypervelocity projectiles is well studied, having been used to capture dust particles by a number of missions (e.g. orbital debris collector on MIR [10], Stardust [11] and Tanpopo on the International Space Station[12]). For each in-

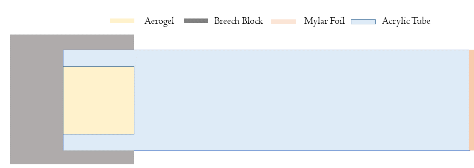

Figure 1: Schematic of the environment chamber.

vestigation we fire 2 shots: one with the atmosphere tube evacuated and one with atmosphere present. By comparing the samples in each case we aim to identify and differentiate those effects caused by atmospheric ablation and those which are caused by the effects of capture. Our initial testing of the environment chamber used 1 mm stainless steel projectiles accelerated to 3 km/s. We have now begun to study 3 mm olivine (Fo90) crystals as a more realistic micrometeorite analogue. The projectiles are characterized before and after shooting optically, by Raman Spectroscopy and SEM EDX.

3. Results

In our initial studies with 3 mm stainless steel projectiles, we demonstrated the survivability and reusability of the chamber. We were also able to film the projectile's passage through the atmosphere and subsequent interactions using low specification high speed cinematography (Figure 2). Initial results using the olivine projectiles showed that using the current set up a maximum projectile velocity of $1\ \mathrm{km\,s^{-1}}$ was obtainable before the Mylar foil seal resulted in the catastrophic disruption of the olivine.

Figure 2: Showing the light flash recorded by the Panasonic HX-WA30 high speed camera during the test shot of the environment tube. The projectile is travelling from right to left.

4. Summary

Preliminary results show the environment tube permits the simulation of high speed atmospheric entry, with work ongoing to enable hypervelocity entry by modifying the Mylar seal.

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EPSC Abstracts
Vol. 12, EPSC2018-397, 2018
European Planetary Science Congress 2018
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Geminid meteor shower activity should increase

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Abstract

Mathematical modelling has shown that activity of the Geminid meteor shower should rise with time, and that was confirmed by analysis of visual observations 1985–2017.

1. Introduction

The Geminid meteor shower is an annual major shower with the maximum activity on December 14. In 2017, asteroid (3200) Phaethon, recognised parent body of the stream, had a close encounter with the Earth on December 16. When the Earth passes closer to a parent body orbit of a meteoroid stream, an increased activity of the shower is expected. We elaborated the model to see, if it is the case, and made a comparison with visual and video observations of the Geminid shower activity [1].

The origin of the parent asteroid is not clear. Dynamical and spectral properties of Phaethon seem to support the asteroidal nature of the object. However modelling of the Geminid stream formation has shown that a cometary scenario [2] is in very good agreement with the observed structure features of the shower, as opposed to the collisional or eruptive scenarios. Lately (in 2009, 2012 and 2016) a weak recurrent activity in perihelion was observed [3]. Thermal fracture/decomposition of the surface was considered the most probable mechanism for the activity [3], but it can not be the main Geminid source [4, 5]. So we used the cometary stream model, presented in [6].

In this report we are going to present our study [1], and to compare our theoretical expectations and observations of the Geminids 2017.

2. Model

We used one a model with meteoroids of the 'visual' mass of 0.02 g from [6] and extended it until 2025 January 1. The model consists of 30 000 meteoroids generated around starting epoch JD 1720165.2248 (perihelion passage) using, as we mentioned, the cometary scenario of ejection. For details of the model, method, and references, see [6].

Why activity should increase? The answer is clear from Fig. 1. Phaethon's node and the mean orbit of the stream (i.e. the densest part of the stream) gradually approach the Earth's orbit. So the Geminid shower activity should increase *slowly*. Why we should not expect an outburst? Because the Geminid stream had no replenishment after the initial catastrophic generation [2, 6].

The increase of activity should be replaced by decrease about 2200, when the stream core should intersect the Earth orbit (Fig. 1).

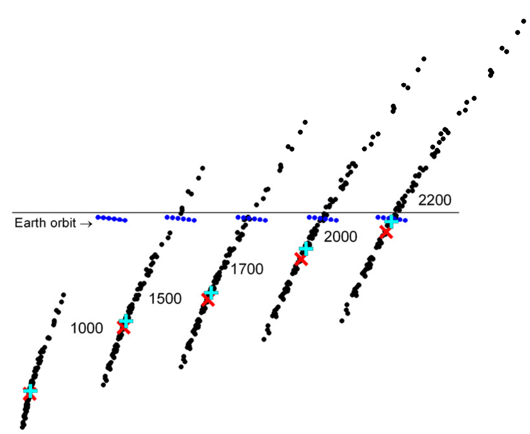

Figure 1: Evolution of the model Geminid stream (100 particles, mass = 0.02 g) cross-section in the ecliptic plane. The figure is modified after [1, fig. 2].

3. Observations

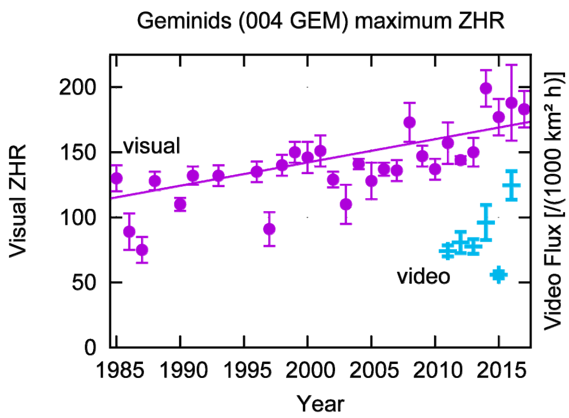

Figure 2: Activity level of the Geminids in 1985–2017. The figure is modified after [1, fig. 3].

Analysis of 60 yr of visual observations (1944–2003) [7] has shown that the shower activity is rather stable. We revisited the analysis using only homogeneous observations, only the peak activity and a constant population index. The result is shown in Fig. 2. We added Geminids 2017 to [1, fig. 3] and we see that the general trend is the same, but the shower activity in 2017 was not extra-high.

4. Summary

We analysed visual observations of the Geminid shower in 1985–2017 around the shower maximum using homogeneous series of visual observations. It was found that the shower activity slowly increases. The same was obtained for video observations (2011–2016). These results were supported and explained by mathematical modelling. Activity of the shower increases because the core of the Geminid stream moves towards the Earth.

Acknowledgements

RGO was supported by grant (N 8.2.12.2018) from `The Tomsk State University competitiveness improvement programme'. This research has made use of NASA's Astrophysics Data System.

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EPSC Abstracts
Vol. 12, EPSC2018-495, 2018
European Planetary Science Congress 2018
© Author(s) 2018

Shock layer radiation of an evaporating meteor

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Abstract

Meteor entry are characterized by complex shock layer physics such as radiation, evaporation of the meteoroid surface and the resulting chemistry process with the air constituents. In this work we present the analysis of a meteor entry using Computational Fluid Dynamic tools where a boundary condition for evaporation is implemented. Moreover the radiative source terms are derived by solving a 1D radiative transfer equations using a tangent slab method.

1. Introduction

The meteor phenomenon occurs daily around the planet Earth. Although a large number of the arriving particles are considered dust (micron-size grains) occasionally a large bolide burst into the atmosphere. The latter may represent a threat to the population as experienced during the Chelyabinsk event in 2013 [1]. At the range of velocities typical of meteor phenomena, radiation becomes highly significant, the intense light observed during a meteor entry is mainly due to the radiation of the air and metallic species, where the latter are coming from ablation products. The current models to study meteor entries are focus in the ablation of small particles in the upper atmosphere. They usually rely on a zero dimensional approach providing lack of an accurate treatment of the particle interaction with the atmosphere, from the fluid dynamic point of view. Therefore, for meteoroids big enough to survive this first phase of the atmospheric entry, a different approach has to be sought.

In this work we propose to study the meteor ablation with a numerical approach similar to those used in the aerospace community to model the gas-surface interaction over Thermal Protection System (TPS) materials. The flow governing equations are solved through a CFD code where a special boundary condition for evaporation is considered and a radiation solver is coupled. The flow properties are computed with the VKI physico-chemical library (Mutation^{++}).

2. Methodology

The 1D Stagnation-Line solver solves the Navier-Stokes equations along the stagnation line of spherical or cylindrical bodies. This model leads to an efficient way to calculate hypersonic flows with low computational costs.

The closure of the governing equations is done by the Mutation^{++} library built at the VKI [2] where thermodynamic properties are computed by the Rigid Rotor Harmonic Oscillator model while transport properties are derived by the Chapman-Enskog expansion from Kinetic Theory.

The evaporation of a molten layer can be modelled by limiting the control volume to a infinitesimal thin lamina where the surface is located. Typically mass conservation for the generic species i can be written in terms of a surface mass balance (SMB).

To solve this balance a suitable model to compute the surface reactions is needed, which in general can be solved by heterogeneous finite-rate chemistry. The evaporation/condensation of the material is estimated by the Knudsen-Langmuir law.

The surface temperature can also be estimated by computing an energy balance of the incoming and outgoing energy fluxes.

Energy and chemical (photoionization and photodissociation) source terms to account for radiation are included into the Navier-Stokes. These source terms are computed by solving the radiative transfer equations (RTE). Solving the RTE by conventional methods such as Line-by-Line (LBL) becomes computationally very expensive for complex molecular spectra. In this work we use a hybrid statistical narrow band model (HSNB) [3] which as the feature of presenting an accurate description of the radiative flux with low CPU by dividing the spectra into narrow bands and compute the intensity in terms of averages.

3. Results

As a preliminary study we considered a 1 dm radius ordinary chondrite at 60 km with a velocity of 15 km/s.

A two-temperature model was used for these simulations, i.e., T $=$ T$_{rot}$ and T$_{vib}$ $=$T$_{ele}$ and the wall temperature was imposed at 2600 K. The choice of this temperature was based on experimental and numerical observations of a melting ordinary chondrite [4].

A sensitivity analysis was initially made to the evaporation and condensation coefficients, in the Knudsen-Langmuir law, to evaluate the overall mass injection into the flow. The chosen coefficients are shown in Table 1.

Table 1: Coefficient parameters

Case #	coefficient
Case 1	α_{evap} = 0.1, α_{cond} = 0.1
Case 2	α_{evap} = 0.1, α_{cond} = 0.0
Case 3	α_{evap} = 1.0 , α_{cond} = 1.0

For all the cases the major vapour species is Na followed by NaO. For case 1 and 3 the evaporation rates are similar (around 10 $\%$ of Na at the surface) while for the case 2 the concentration of Na is represents almost 60 $\%$ of the total vapour since the choice of the condensation coefficient does not allow for this species to condensate. Since Na has a low ionization energy it quickly forms Na^+. Even though in the case 3 the evaporation coefficient is ten times higher than case 1 also the condensation coefficient follows the same trend. Meaning that the evaporation is higher but the condensation is also higher creating a balance between evaporation/condensation fluxes. The injection of mass shifts the shock position upstream due to the outgoing blowing velocity from the surface.

The final analysis was to include radiative source terms and to compare a 1 dm and 1 m radius OC at the same conditions as the one above for the case 1. For both radii it was observed a decrease of temperature in the shock layer due to the radiant emission increasing the heat flux at the surface. The radiative field becomes stronger for the 1 m case due to a larger shock layer. The ablation rate did not change significantly since the wall temperature as chosen to be the same as the first analysis. Interestingly, due to the strong shock emission the flow upstream of the shock undergoes photochemical processes. These processes leads to photoionization and photodissociation reactions increasing the electron density. In our case only photoionization mechanisms are considered. Moreover a departure from thermal equilibrium is also observed in the free-stream. For the 1 m radius body this departure is strong enough to have an exchange of energy between the internal and translation mode rising the translation temperature. This rise of the translation temperature leads to a strong dissociation of O_2 since the chemical rate is controlled by a geometrical temperature $T = \sqrt{TT_i}$.

4. Concluding Remarks

In this work a flow/radiation/ablation methodology was presented to study the meteor entry. It was observed that a stronger radiative field for bigger bodies which explains the stronger luminosity for bolides. In this case the surface energy balance was not considered. Further analyses will be made to compute the energy balance considering the incoming radiative flux to the surface.

Acknowledgments

This research is sponsored by the Belgian Research Action Through Interdisciplinary Networks “METRO: Meteor trajectories and origins”. Research of B. Dias is sponsored by fellowship from the “Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture.”.

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EPSC Abstracts
Vol. 12, EPSC2018-518, 2018
European Planetary Science Congress 2018
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Numerical modelling of meteoric dust transport in Earth atmosphere

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Abstract

This paper is concerned with numerical modelling of atmospheric dynamics of meteoric dust. The simulations of dust particles are carried out via sphere approximation. Differential equations for movement and heat transfer are solved in a parallel collisionless manner using Lagrange variables via Runge-Kutta methods. The drag force of atmospheric air is computed via Henderson formula. The parameters of surrounding gas are calculated from standard atmosphere model. Real meteoric particles are modelled by computational representatives.

1. Introduction

It is known that the influx of extraterrestrial matter comes in two categories, namely meteoroids and cosmic dust, e.g. [1]. While the former smoothly slips into the latter one, it is plausible to consider the cosmic dust to be composed from individually unobservable particles. The estimations [2] show that the 20 percent of total mass influx originates from particles with initial masses in the range from 10^{-6} up to 10^{-5} g. However, the particle influx is not limited to cosmic dust, as the fine-grained product of meteoroid fragmentation also contributes to particle influx. The dispersed fraction like this has the distinctive feature of prolonged deposition in the planetary atmosphere due to near equilibrium of gravity and lift forces. The similar feature is also shared by the volcanic ash particles but on a larger spatial scale. The necessity to estimate propagation of dispersed admixture comes from the fact that the high volume concentrations of millimeter particles present a hazard to a safety of airborne vessels, especially for turbine engines. There are several known well documented incidents with aircraft, the most notable of which are the cases of British Airways Flight 9 on 24 June 1982 [3] and KLM Flight 867 on 15 December 1989 [4]. Moreover, the plumes of much lesser micrometer-sized hard particles also can be dangerous to high altitude supersonic and hypersonic vessels due to thermo erosion of the frontal heat shield (e.g. [5], [6]).

2. Mathematical Model and Numerical Simulation Algorithm

The dispersed admixture dynamics in the atmosphere is usually simulated numerically as a discrete particle ensemble propagating through the gaseous phase. Since we investigate the long term phenomenon, the particles of interest are considered to have low velocity relative to surrounding carrier media. Therefore, we suppose the carrier gas is not affected by the discrete phase, resulting in its computational model to be decoupled from the particle simulation. In addition, due to large spatial scale of an ensemble, we concerned with a study of specific volumetric concentrations of the averaged particle groups. There are two approaches to simulate admixture evolution in carrier phase using Eulerian and Lagrangian variables respectively [7]. The first class of methods discretizes the field of concentration on computational grid and apolies differential transport equations approximated with finite difference schemes. However, this technique suffers from high artificial diffusion leading to significant admixture mass loss and boundary smearing in the simulation process. The second class of methods represents the field of concentration with set of generalized markers, each aggregating some of the initial particles. Therefore, we implemented a Largrangian model for the cloud of meteor dust. The dynamics of spherical particle-representatives is approximated via a system of differential equations for movement. This system of equations in Lagrange variables is integrated via Runge-Kutta methods. The particle trajectories with respect to the reference ellipsoid WGS-84. To account for possible shock-scale perturbations of the surrounding atmosphere, the drag force of atmospheric air is computed via Henderson formula valid for wide ranges of Reynolds and Mach numbers. The parameters of surrounding gas are obtained from the COSPAR International Reference Atmosphere (CIRA-86), which includes monthly zonal wind chart. To increase perfomance of the method we implemented parallel processing in the form of multithreaded multicore computations. Since the classic Lagrangian methods with fixed amount of markers are unable to track concentration quantities lesser than that of single marker, we also used hybrid 'dipole' method, where each computational particle can split into lesser particles when it's poles diverge far enough.

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EPSC Abstracts
Vol. 12, EPSC2018-546, 2018
European Planetary Science Congress 2018
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Regular and transitory showers of comet C/1979 Y1

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Abstract

We mapped the whole meteor shower complex of the long-period comet C/1979 Y1 (Bradfield). The modeled stream of the comet approaches the Earth's orbit in two filaments which correspond to two regular (annual) showers and in several other sections which survive only during a limited period (transitory showers). One of the regular predicted showers coresponds to the July Pegasids, No. 175 in the IAU MDC list of showers and one of the transitory filaments to the γ-Bootids, shower No. 104 [1].

Summary and Conclusions

For five perihelion passages of the parent comet in the past, we modelled associated theoretical streams, each consisting of 10 000 test particles, and followed their dynamical evolution up to the present. The models were characterized by a variety of values of free parameters, evolutionary time t_{ev} and the strength of the Poynting-Robertson drag β, and were used to predict a part, or parts, of the stream that can collide with the Earth. The predicted showers were compared with their observed counterparts separated from photographic, radio, and several video databases.

We confirm the earlier suggested generic relationship [2] between the studied parent comet and #175 July Pegasids, which we identified to one of our modeled filaments. The other regular filament corresponds to a daytime shower with the mean radiant situated symmetrically to the July Pegasids with respect to the apex of the Earth's motion. This shower is not in the IAU MDC list of meteor showers, but we separated it from the CAMS [3] and SonotaCo [4] databases, and suggest naming it α-Microscopiids.

These two filaments of the stream are deflected away from the Earth's orbit when the stronger influence of the Poynting-Robertson drag is considered. But it makes the stream cross the Earth's orbit in other sections. Corresponding showers are, however, only expected to survive during a limited period and to consist of particles of sizes in a narrow interval. We identified one of these transitory filaments to the #104 γ-Bootids.

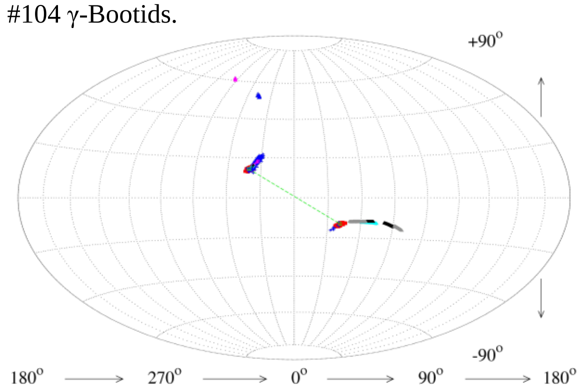

Figure 1: Positions of radiants of theoretical particles in regular filaments (red full squares – the model for t_{ev} =10 kyr), and transiting filaments crossing the Earth's orbit (individual colors – blue, violet, cyan, black, and gray – distinguish between the radiants in the models for t_{ev} = 80, 40, 20, 10, and 5 kyr, respectively). The radiants are shown in the modified ecliptical coordinate frame with the center in the apex of the Earth's motion.

Acknowledgements

This work was supported by the Slovak Research and Development Agency, contract No. APVV-16-0148 and by the Slovak Grant Agency for Science, grant No. VEGA 2/0037/18.

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EPSC Abstracts
Vol. 12, EPSC2018-554, 2018
European Planetary Science Congress 2018
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Southern sky meteor showers – AMOS data

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Abstract

The ongoing video observations have caused a huge increase in the reporting of new meteor showers, the number of which in the IAU MDC list [1] has grown to more than 900. Since the southern sky observations are still significantly rarer than observations of the northern sky, only less then a quarter of the established showers have their radiants on the southern sky. In the working list, there are about 800 showers, the confirmation of which remains open, owing to the low number of southern sky data in the databases.We present our meteor data contribution from the new stations in the Atacama Desert in Chile, established as part of the AMOS project of the Comenius University in Bratislava, Slovakia, which have been in operation since March 2016.

1. System AMOS

The AMOS (All-sky Meteor Orbit System) cameras [2] were developed at Comenius University's Astronomical Observatory in Modra, Slovakia. Their astrometric precision was calibrated using several fireballs observed within the European Fireball Network [3]. The AMOS cameras installed in the Atacama Desert operate fully automatically; their field of view is 180°×140° and the output digital resolution 1600×1200 pixels, with a rate of 20 frames per second.

2. Search for meteor showers

For our analysis, we also use, except for the AMOS data from the Atacama Desert, AMOS data from the Canary Islands [2], which partly cover the southern sky. To separate the potential showers / meteor clusters, we use a method based on the mean orbital characteristics of meteors but also considering their geophysical parameters, suggested by Rudawska et al. [4]. Found showers are compared with the showers from the IAU MDC list. Furthermore, we investigate their possible identification with the theoretical modelled streams of several comets, associated meteor showers of which have predicted radiant areas on the southern sky [5, 6, 7].

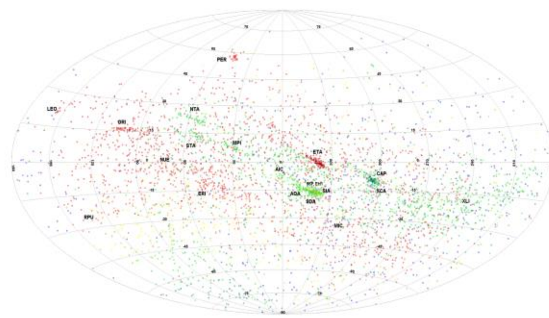

Figure 1: The radiant distribution of 4463 double-station meteors by AMOS cameras in Atacama, Chile.

Acknowledgements

This work was supported by the Slovak Grant Agency for Science VEGA, grants No. 1/0596/18 and by the Slovak Research and Development Agency, contract No.APVV-16-0148.

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EPSC Abstracts
Vol. 12, EPSC2018-582-1, 2018
European Planetary Science Congress 2018
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The production of nitric oxide by centimetre-sized meteoroids in the upper atmosphere

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Abstract

Nitric oxide (NO) is a very important minor species in the upper atmosphere, and a critical indicator of energy deposition in the lower thermosphere because of its formational pathways. However, it is important to constrain additional sources of NO, such as meteoroid generated hypersonic flows below 95 km altitude, in the upper mesosphere-lower thermosphere (MLT) region of the atmosphere. In this study, we estimate of the upper boundary of the cumulative mass of NO produced annually by cm-size meteoroids. Our results suggests that this upper boundary of NO production is significantly lower than that reported in previous early studies.

1. Introduction

All optically detectable meteors, as well as many of the stronger radio-detectable meteors, produce shockwaves during the lower transitional flow regimes in the MLT (Mesosphere-Lower Thermosphere) region of the atmosphere, at altitudes between 75 km and 100 km [1]. Meteor generated shock waves can modify the surrounding atmosphere and produce a range of physico-chemical effects [1]. Some of the thermally driven chemical and physical processes induced by meteor shock waves, such as nitric oxide (NO) production, are less understood. Any estimates of meteoric NO production depend not only on a quantifiable meteoroid population with a size capable of producing high temperature flows, but also on understanding the physical properties of the meteor flows along with their thermal history. These combined factors were the sources of significant uncertainties in assessing meteoric NO pro-duction in the MLT region in early studies (e.g. [2]). Nitric oxide, a trace species in the upper atmosphere, plays an important role in the energetics of the MLT, especially in the lower thermosphere where it exhibits the highest con-centration [3]. Nitric oxide also emits efficiently in infrared at 5.3 μm, and as such, it is also an important source of radiative cooling in the upper atmosphere (e.g. [4]). However, the mechanisms responsible for N2 dissociation (e.g., soft X-rays, UV radiation and high energy auroral electrons) are typically less efficient in the MLT below 95 km, and other sources of NO at those altitudes, such as meteoroid high temperature flow fields, require better quantification. We examined the capacity of centimetre-sized meteoroid hypersonic flow fields to produce NO via the Zel'dovich mechanism, at altitudes of 80-95 km and sought to establish the upper mass boundary of meteoric NO deposited in that region of atmosphere.

2. Analytical Approach

The two main reactions, collectively known as the Zel'dovich mechanism, that are primarily responsible for the NO production in the incipient high temperature hypersonic flows, in the range of approximately 2,000 – 10,000 K, can be written as:

$$N2 + O \rightarrow NO + N \quad (1)$$

$$N + O2 \rightarrow NO + O \quad (2).$$

In our study, we assume the following: (i) the value of mole fraction of the NO production remains constant for both endothermic Reaction (1) and temperature independent Reaction (2); (ii) the NO production is bound within the volume of bright meteor plasma train with an initial radius r_0 [5]. Consequently, the mass of produced NO is computed from 80 to 95 km altitude within the plasma volume with the height dependent the initial radius of a bright meteor train (e.g. [6]). The full treatment, the assumptions implemented in the analytical approach and the methodology are presented in [7]. We then use the most recently published flux rates to obtain the estimate for the annual NO production by cm-sized meteoroids [8]. In order to validate our assumption regarding the centimetre-sized meteoroid NO production boundary governed by r_0 of bright meteors, we take advantage of the characteristic or blast radius (R_0), which represents the region of maximum energy deposition per unit path length and is written as (e.g. see [1]):

$$R_0 = (E_0/p_0)^{0.5} \quad (3).$$

In this expression, E_0 is the energy deposited by the meteoroid per unit path length and p_0 is the ambient pressure [1]. We subsequently investigated the effect of impact velocity and size of ablating meteoroids.

3. Conclusions

Our study suggests that the upper mass limit for NO produced by centimetre-sized meteoroids is in the range of 100 tons/year. This value is significantly smaller than the mass estimated in the early studies [2,9]. Further interpretation of our results demonstrates that the maximum cumulative annual production of NO by meteoroids with sizes capable of sustaining high temperature flows cannot exceed 1,000 tons annually. This is primarily due to a drastically revised meteoroid annual mass influx [1]. We also discuss the reasons why cm-sized meteoroids are the most efficient producers of NO.

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EPSC Abstracts
Vol. 12, EPSC2018-585-2, 2018
European Planetary Science Congress 2018
ⓒ Author(s) 2018

Shock waves generated by meteoroids impacting the Earth's atmosphere: An up-to-date state of knowledge in the field

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Abstract

Shock waves and the associated phenomena generated by strongly ablating meteoroids in the lower transitional flow regime of the Earth's atmosphere are of great interest to the scientific community, yet remain the least explored aspect of meteor science. Here, we discuss a comprehensive review covering meteor generated shock waves in the atmosphere.

1. Background and Motivation

The problem of shock waves generated by meteoroids as they interact with the Earth's atmosphere at hypersonic speeds is of great interest to the scientific community, especially from the perspective of planetary defense. The spectacular impact and subsequent airburst of the Chelyabinsk bolide in 2013 served as a sober reminder of the destructive potential of extraterrestrial bodies. While certain subdisciplines of meteor science have been receiving a great deal of attention and are well represented in literature (e.g. optical and radar observations, orbit analyses, meteorite falls), the problem of shock waves has been largely neglected. In fact, a comprehensive and up-to-date re-source encapsulating the advancements in meteor physics, in particular the shock wave phenomena associated with the meteoroid impacts into the Earth's atmosphere has been lacking until now. Much of the knowledge gained over the decades has been scattered through time, space, and disciplines. For example, some early works on hyper-sonic flows applicable to meteors remain in the domain of "grey" literature (thus are easy to fall into obscurity), while more recent developments in re-entry remain in the realm of the rarefied gas dynamics and hypersonic flow communities with little to no cross-over to meteor science. We present the up-to-date and comprehensive review of meteor generated shock waves in the Earth's atmosphere with the aim to build a go-to resource for anyone interested in the meteor phenomena.
The review paper, currently in press in Advances in Space Research [1], presents the following topics in great depth:

- Meteoroid entry, the Knudsen number, and flow regimes;
- Hydrodynamic shielding and implications for the formation of shock waves;
- A detailed description and review of meteor generated shock waves.
- To fully encapsulate the field of meteor generated shock waves, we also discuss the related topics of interest to the scientific community interested in meteor generated shock waves:
- Analytical and modeling approaches;
- Airbursts and the NEO threat;
- Radar and infrasound observations.

2. Summary

We present a detailed review of meteor generated shock waves in the Earth's atmosphere with the aim to provide an up-to-date state of the field and a comprehensive resource for anyone interested in studying the phenomena associated with meteor generated shock waves. While meteor science might be considered a mature science, we suggest that there is much more work to be done and many important scientific questions to be answered.
Some of these questions are:

- Resolving the altitudes where cm-sized meteoroids generate shock waves as a function of velocity, size and composition;
- Understanding the physico-chemical aspects of meteor shock wave phenomena in the near and far field ambient atmosphere around the meteor and its physico-chemical impact on the mesosphere and lower thermosphere (MLT);
- Development of the methods for meteor shock wave detection at the altitudes where they form;
- Understanding the risks and further constraining the lower boundary of sizes, compositions and velocities of large objects that create shock waves in the lower atmosphere and pose a potential hazard;
- Understanding the hazards of meteor generated shock waves and their effects in the mesosphere and lower thermosphere (MLT) region of the atmosphere to future frequent space travel.

We encourage the members of scientific community to embark on deciphering these and many other interesting questions that remain to be answered.

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EPSC Abstracts
Vol. 12, EPSC2018-728-1, 2018
European Planetary Science Congress 2018
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Analysis data of atmospheric trajectory 8916 radio meteoroids registered in HisAO

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As we know, all previously published catalogs of radio meteors [1], [2], [3], [4], [5], [6], [7], [8] compiled on the basis of ground radar observations contain only the terminal value of the recorded stellar magnitude or the masses of meteoroids is given. Therefore, it seems interesting to have a catalog of radio meteors, which, along with kinematic characteristics calculated using more accurate methods, also include data on the atmospheric trajectory (altitudes, linear electron density, radar magnitude and mass) of each individual meteor.

Thanks to the support of the ISTC (Project T-2113), a catalog was created to base the results of radar observations of meteors from four points in the HisAO Institute of Astrophysics of the Academy of Sciences of the Republic of Tajikistan.

In this paper, we present the results of the calculation of some physical characteristics and analysis of the data of the atmospheric trajectory of 8916 radio meteors entering the first part of the Catalog of Radiant's, Velocities, Orbits and the Atmospheric Trajectory of Meteoroids observed from December 1968 to December 1969. Meteors entering the catalog had the form of amplitude-time characteristics (AVC), analogous to intermediate or excessive types of meteor trails. The key data on the atmospheric trajectory of the meteor are: a) the height of the mirror reflection point at the center (approximately the height of the maximum ionization), b) the linear electron density q, c) the radio emission of the meteor M and d) its mass m_o.

The main initial parameters necessary for calculating the physical characteristics of meteors are the altitudes and obtained values of echo duration. The value of linear electron density q for the trails of intermediate and overdense type is usually calculated by a well-known formula:

$$q = \frac{\left(\tau + r^2/_{4D}\right)D}{A\lambda^2}, \qquad (1)$$

Here τ is duration of radio echo, A = $e^2/\ 4\pi^2\ mc^2$, λ - wavelength; e, m - charge and mass of the electron, c - speed of light, r - initial radius of the trail, and D - coefficient of ambipolar diffusion.

Equation (1) is valid when the decrease in electron concentration of the trail occurs only because of ambipolar diffusion. However, in real-life conditions, along with ambipolar diffusion in the meteor trail of overdense type, the following types of deionization have influence: radiative and dissociative recombination, electron attachment to neutral particles, turbulent diffusion, and photolysis. The influence of these processes on the reduction in the duration of radio echo was taken into account by a number of researchers, in particular, by R. Sh. Bibarsov at the Institute of Astrophysics of the Academy of Sciences of the Republic of Tajikistan [9].

For meteors, whose duration τ is shorter than the time constant of small-scale eddies t (i. e, meteors with τ ≤ t ≤10 s), the formula for calculating linear electron density with allowance for attachment and ambipolar diffusion has the following form [9]:

$$q = \frac{\left(\tau e^{-k\tau} + r^2/_{4D}\right)D}{A\lambda^2}, \qquad (2)$$

where A = $7.1\mathrm{x}10^{15}$ cm^{-1}.

To apply formulas (1) and (2) in calculating the value of linear electron density, in addition to the measured value of radio-reflection duration τ, data on the value of the initial radius r, the ambipolar diffusion coefficient D, and the electron attachment velocity to neutral particles k are required. To calculate the values of r, D, and k, we used well-known formulas [10]:

$$r = 1.47 \times 10^{-10} \times V^{0.65} \times \rho^{-1}$$

$$\log D = 0.079 h_i - 6.6\ , \qquad (3)$$

$$\log k = 4.99 - 0.07 h_i\ ,$$

where ρ is the density of atmosphere at height h_i. The height of specular reflection point for the central point of observation is determined by the known formula

$$h = R\ \cos Z + \Delta h\ , \qquad (4)$$

Here R is the distance of the reflecting point, Z is the zenith distance of the reflecting point at the central point, Δh is correction of the height taking into account the curvature of the Earth and the observation point's elevation above sea level. The heights of reflection points Δh_i on the meteor trail relative to the height of the central point for each meteor are found by the formula

$$\Delta h_i = V\ \Delta t\ \cos Z_r\ , \qquad (5)$$

where V is meteor velocity and Z_r is the zenith distance of the radiant.

Knowing the value of linear electron density makes it possible to calculate the radio magnitude of the meteor and it's mass. Usually, radio magnitudes are calculated using the known formula:

$$M = 35 - 2.5 \log q\ , \qquad (5)$$

where q is the value of the linear electron density in el/cm. However, the opinion of researchers on the relationship between the radio magnitude of the meteor and its velocity varies significantly. In particular, in [11] by results of simultaneous video-radar observations established the relationship between the radio magnitude and the value of linear electron density which has the form:

$$M = (33.72 \pm 1.2) - 2.5 \log q\ , \qquad (6)$$

where q is the value of the linear electron density in el/cm.

Pecina in [12] using the results simultaneous two-station video and radar observations of Perseids in 1998 and 1999 in the Czech Republic for 18 meteors between magnitude $+0.4^m$ and $+6.0^m$ found the relation

$$M = 37.5 - 2.5 \log q \;, \tag{7}$$

The equation (5) represents as averages between the equations (6) and (7). Hence we for transition from linear electronic density to star magnitude used the equation (5). When calculating the height of homogeneous atmosphere H* at the specular reflection point, the following two polynomial series are used by [13]:

1) $H^* = 0.0015\, h^2 - 0.2978\, h + 19.76$ for the height range of 60 <N <89 km.

2) $H^* = 0.007\, h^2 - 1.381\, h + 69.12$ for the height range of 90 <N <125 km.

Calculations of the mass of radio meteor used ionization coefficient values, calculated from the results of combined radar-optical measurements for a wide range of velocities [10]. The relationship between ionization coefficient and velocity, according to combined optical and radar observations was determined [10] to be

$$\beta = 10^{-7.73} \times V^{3.88} \tag{8}$$

where V is expressed in km/s.

The formula for calculating the mass of meteoric bodies by the radio method has the following form [10]:

$$m_0 = \frac{3H^* \mu q_m}{4\beta \cos Z_r}, \tag{9}$$

where H* is the height of the homogeneous atmosphere, μ is the mass of the meteorite atom, β is ionization coefficient, Z_r is zenith distance of the radiant.

Formulas (2 and 9) make it possible to calculate the mass of meteors on the basis of the measured values of the radio echo duration, taking into account the fragmentation and deionization processes.

The results of calculating the logarithm of linear electron density, radio magnitude, and logarithms of meteoroid mass are also presented in Figs. 1-3. According to Fig. 1, the range of logarithms of linear electron density is the interval of 11.8-14.6 el/cm. The maximum in the distribution is at 12.8÷13.00 el/cm. The range of a radio magnitude is located basically in the interval of +5.5 ÷ -1, and logarithms of meteoroid mass is in the rang -3.5 ÷ 2. Maximum in logarithms of distribution of mass of a meteoric body are in an interval -2.5 ÷ -2.

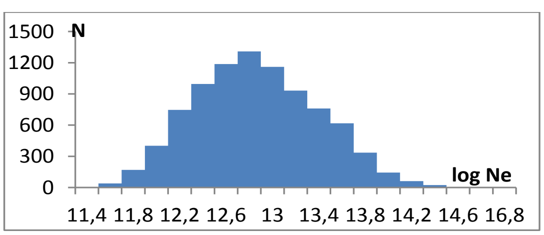

Fig. 1. Observed distribution of linear electron density of the 8916 radio meteors.

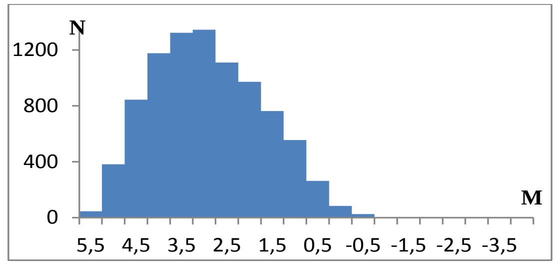

Fig.2. Observed distribution of radio magnitude of 8916 radio meteors.

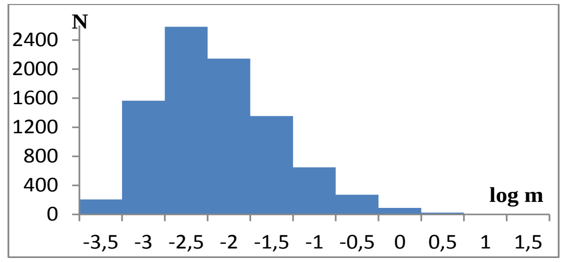

Fig.3. Observed distribution of logarithms of meteoroid mass of the 8916 radio meteors.

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EPSC Abstracts
Vol. 12, EPSC2018-775, 2018
European Planetary Science Congress 2018
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Extra-terrestrial meteors: A review

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Abstract

We review the history, status and future prospects of meteor astronomy on planets other than the Earth. Recent high-profile events - impact flashes on Jupiter, the Siding Spring encounter with Mars - brought this branch of meteoroid studies into the limelight. We discuss the value of non-Earth observations: discovering new streams, comparative studies of ablation physics, sporadic activity and multi-planet streams. Next, we summarise the expected characteristics of meteors relevant to observations on and off the Earth, considering both the optical phenomenon of the meteor itself as well as the after-effects of meteor activity in general (ie ionised metallic layers in the upper atmosphere). Next, we point out serendipitous detections of either confirmed or putative meteors, followed by recent detections of the Siding Spring shower at Mars and of fireballs at Jupiter. Finally, we discuss future prospects: expected near-term observations as well as missions & instruments planned or in the conceptual stage.

Acknowledgements

Astronomical research at the Armagh Observatory and Planetarium is funded by the Northern Ireland Department for Communities (DfC).

EPSC Abstracts
Vol. 12, EPSC2018-812, 2018
European Planetary Science Congress 2018
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Validation of Knudsen numbers and flow regimes for well-characterized centimetre-sized meteoroids

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Abstract

For centimeter-sized meteoroids impacting the Earth’s atmosphere, the formation of a vapour cap and eventually a shock wave creates a physical scenario that is still to be fully understood. This work analyses the flow regimes for such bodies and illustrates how infrasound information can provide relevant information in meteor science.

1. Introduction

In 1974 Revelle [5, 6] outlined a theory to study the weak shock that occurs after the decay of a highly non-linear strong shock wave created as a result of the meteoroid’s passage through the atmosphere. The low frequency (<20 Hz) generated by a cylindrical shock wave [7] can be detected from ground detectors and eventually provide relevant information on the associated meteor phenomena (the optically detectable light production due to the meteoroid ablation [2]). This theory was later validated with a large meteoroid data set for which the infrasound information was linked to visual observations [8]. Additionally, the altitude of the meteor generated shock wave was constrained in [7] by finding the point along the meteor trajectory from which infrasound signal originated. Although this altitude is not diagnostic of the initial onset of the shock wave, it represents the earliest known point for which the shock wave is determined to exist.

In this work, we demonstrate that this information is valuable in extending our understanding of the meteor flow regimes of impacting meteoroids. Additionally, we show that the use of a flow regime scale that accounts for the physics of the event is more adequate than a simplistic general approach. A sample of 24 well constrained centimeter-sized events are taken from [8] to carry out our study. To our knowledge, this is the only well-documented and well-constrained set of such events to-date.

2. Flow regimes

When a centimeter-sized meteoroid enters the Earth’s atmosphere at hypersonic velocities, the incoming atmospheric molecules ejects large number of meteoroid atoms. The accumulated number of particles in front of the meteoroid creates a vapour cap that acts as an “hydrodynamic shielding” [4] and reduces the number of high energy impacts. At lower altitudes, when the pressure of the vapour in the flow field surrounding the meteoroid significantly exceeds that of the surrounding atmosphere (at least two orders of magnitude), the vapour gas expands radially behind the shock envelope and as such, can be considered as a hydrodynamic flow [4]. In a simple sense, that creates a shock discontinuity where the pressure, density and temperature experiences large jumps. As a consequence, the mean free path behind the shock discontinuity changes and hence the flow regime shifts [9].

The flow regimes are classified according to the Knudsen number (Kn), which is a dimensionless parameter defined as the ratio between the mean free path of the gas molecules (λ) to a physical length of the body immersed in the gas ($Kn=\lambda/L$). In order to account for the mean free path of the reflected (evaporated) meteoroid atoms relative to the impinging particles, the reference frame in this study is set at the meteoroid surface [1]. Furthermore, we use two different flow regime classifications to understand the differences when including possible viscous effects in the shock layer (the region between the shock wave and the meteoroid surface). On one hand, the classification outlined by Tsien [10] includes the evolution of the Reynolds number to determine the meteoroid flow regime evolution. On the other, we consider the more general Knudsen scale that only accounts for the number of intermolecular collisions within a specific time.

3. Conclusions

Our results show that most of the meteoroids included in our sample are between slip-flow and the continuum flight regime conditions [3]. Despite some minor discrepancies, the results derived from the two classifications (Tsien's and general Knudsen scale) are quite similar. Furthermore, we analyse the effect of varying some initial assumptions made on the general physical parameters (e.g., bulk density, meteoroid surface temperature, negligible deceleration) that may slightly vary for each sample member, only to find minor discrepancies [3].

We note that the scale outlined by Tsien [10] accounts for those parameters that have the largest influence in the results (i.e., the meteoroid entry velocity, viscosity, etc.) as these are held in the *Re* number. This suggests that the use of the Tsien's scale is more appropriate for this kind of study. Finally, we compare our results to the results obtained in [4] for a Leonids meteoroid in order to validate our conclusions.

Acknowledgements

JMTR thanks the support of the Spanish grant AYA2015-67175-P. EAS acknowledges the Natural Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellowship program for supporting this project. MG acknowledges support from the ERC Advanced Grant No. 320773, and the Russian Foundation for Basic Research, project nos. 16-05-00004, 16-07-01072, and 18-08-00074. MMI study was done in the frame of a PhD. on Physics at the Autonomous University of Barcelona (UAB).

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EPSC Abstracts
Vol. 12, EPSC2018-826, 2018
European Planetary Science Congress 2018
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Meteor activities within the BigSkyEarth COST Action: enabling new approaches in modeling and observations

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Abstract

Technological advancements in observing techniques in meteor science are changing quality of research in meteor science. This includes new meteor detection strategies, as well as more reliable simulations of studied meteors. In this contribution we provide an information on some new techniques for observation and simulation of meteors that comes from the cooperation in COST Action BigSkyEarth.

1. Introduction

BigSkyEarth COST Action focuses on building a transdisciplinary network of researchers from area of astrophysics, geophysics, planetary science, and computer science (currently includes cooperation of people from more than 30 countries), with the main ambition to support their collaboration in the new era of Big Data processing of data coming from new measurements and detection sites. BigSkyEarth networking tools represent an excellent platform for discussion on improvements and collaborations in order to develop novel approaches and techniques. The cooperation of scientists in BigSkyEarth emergently created a group of researchers focused on meteor science, which were able to bring new ideas for simulation and observation of meteors, some of them are described in the next chapter.

2. Novel methods and techniques

In this section we shortly describe selected cases of novel techniques related to observation and simulation of meteors, which emerged thanks to cooperation of scientists in BigSkyEarth.

2.1 Detection of meteors from orbit and stratosphere

Within the framework of the JEM-EUSO mission project and its precursors, including the Mini-Euso mission scheduled for launch in 2019, studies are being carried out for the observation of bright meteors from ISS [3]. This can constitute a useful synergy with the activities of several networks of ground-based observers. Moreover, in this case the motion of the ISS can be used to reconstruct 3-D trajectory of meteors and fireballs in some cases. The possibility to detect some classes of WIMP particles, expected to produce signals similar to very fast meteors, is also analyzed. There are also cooperative activities within BigSkyEarth in order to put meteor detection cameras on the top of a new generation of rigid airships, which are developed by Hipersphera (https://hipersfera.hr/). This attempt would lead to the improvement of the observing conditions due to a higher altitude and changes in the observing location.

2.2 Detection of meteors in sky surveys

Another interesting method for detection of meteors came from the analysis of images collected by large sky surveys, where large fields of view is combined with a high-resolution imaging. This turns to be a unique way for exploring meteor science, where the meteor head is resolved (albeit defocused). BigSkyEarth supported this research on SDSS images [1][2]. First results showed that it is possible to extract significant number of meteors from such surveys due to their large total observing time and sky coverage. Therefore, this new initiative is also studied for the upcoming LSST survey.

2.3 Improved interpretation of meteor's parameters

To reliably interpret large amount of observational data generated by the fireball networks worldwide an attention is given to develop and implement new approaches which adequately account for the actual atmospheric conditions at the concurrent location and heights of a meteor. In [5] authors have recently proposed to tackle this problem by introducing atmospheric corrections into the previously developed model [4]. This approach can be inferred to produce more reliable estimates of the meteor′s characteristic parameters since it uses an improved representation of the atmospheric density. When applied to large data sets, the NRLMSISE-00 empirical atmosphere model [6] can be employed to provide more reliable results. Deeply penetrating fireballs, or other meteor events of special interest, could be further analyzed in more detail on a case-by-case basis using the actual measurements of the pressure profile with height. These data come from the Global Forecast System (GFS) and from the European Centre for Medium-Range Weather Forecasts (ECMWF). In practice, these atmospheric corrections have already aided rapid recovery of the Annama meteorite based on observations by the Finnish Fireball Network.

2.4 Improved understanding of meteor radar reflections

Novel numerical methods are being used to test how the changes in the atmospheric conditions or shape or size of the meteor affect its radar reflections and to explain unexpected features in the measurements. The geometry of the meteor is presented as a rigid obstacle covered by non-magnetized plasma that is modeled as a Gaussian density distribution [7]. The computational model is based on partial differential equations of multiphysical wave equations. To save computing time, the computational domain is truncated by artificial absorbing boundaries or perfectly matched layers and discretized by a three-dimensional nonuniform computational mesh. Instead of a conventional numerical discretization method, the mathematical structures are presented as differential forms and discretized by discrete exterior calculus, which together with explicit time-stepping leads to more efficient simulations than the ones available in today's commercial software products or open-source libraries.

2.5 Monitoring of the ELF/VLF/LF waves

Another interesting new solution is implemented for tracking of alert events, which is combined with meteor detection alerts from the fireball network. In this case, AWESOME (The Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education receiver) represents dedicated observation instrument for monitoring of the broadband ELF/VLF/LF waves, which consists of two magnetic antennas collecting approximately 32 GB of broadband data per day.

Acknowledgements

This article is based upon a collaborative work and support from the COST Action TD1403 "Big Data Era in Sky and Earth Observations" (BigSkyEarth, http://bigskyearth.eu/).

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EPSC Abstracts
Vol. 12, EPSC2018-946, 2018
European Planetary Science Congress 2018
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Impact-classification scheme based on the fireball analysis: a preliminary study

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Abstract

To assist convenient grouping of possible scenarios describing meteoroid interaction with the Earth, we have studied well-observed fireball events and defined the impact-classification scheme enabling analytical interpretation of the results. The used parametrization involves dimensionless expressions, which combine the pre-atmospheric meteoroid properties, together with other characteristic parameters. In this talk, we further demonstrate possible applications of the described scheme, in particular its suitability as a cornerstone of an advanced future model capable to robustly forecast consequences of meteoroids' interaction with the Earth's atmosphere and surface prior to their actual impact with the ground.

1. Introduction

It is widely accepted by the scientific community that near-Earth object (NEO) impacts represent a long term global threat to the collective welfare of humanity. Such impacts have occurred much more frequently in the past. Earth would be heavily cratered if it did not have its geologically active lithosphere, and the atmosphere that effectively shields the planet from all but the larger meteoroids and asteroids.

Solving a problem of estimating risks associated with low-probability high-impact bolide events is often decisionally postponed due to the lack of evidence that such impact would occur 'soon' – if so, there considered to be no necessity to map it in the next years of global political and economical developments. However, while the likelihood of a globally threatening event is low, the statistical expectation (i.e., the product of the probability of the occurrence of an impact and the cost associated with its occurrence) is realistic due to the catastrophic consequences caused to the entire ecosphere [1].

In recent years, several world-wide initiatives began with the goal of collecting accurate information and improving the present knowledge of the near-Earth environment. These initiatives include dedicated NEO-surveys, such as NEOWISE [2], PanSTARRS [3], and the Catalina Sky Survey [4]. As a result of these large investments into NEO tracking, the past decade has brought impressive improvements in large-scale asteroid discovery. In contrast to these advances, a comprehensive model capable of tracking a hazardous object from its current location in orbit to its intersection with Earth and which would account for all possible scenarios and result in reliable forecasts of regional environmental consequences on the ground is still missing.

2. Bridging the gap

To improve the current understanding of possible outcomes of meteoroid interaction with the atmosphere, we utilize physically-based parametrization described in [5]. The parametrization is based on introducing dimensionless expressions, which combine the pre-atmospheric meteoroid parameters, together with other characteristic parameters and enables unique (case-wise), but also one-solution handling (i.e. uniquely resolvable in mathematical sense) in the analysis of each particular event. These solutions allow us to analyse and compare different events. The ballistic coefficient, α, characterizes the mass ratio, or the drag intensity – it is proportional to the mass of the atmospheric column the meteoroid has to penetrate through to reach the ground divided by the pre-atmospheric meteoroid mass. The mass loss parameter, β, reflects the ratio of the pre-atmospheric kinetic energy of the impactor divided by the energy required to be applied for its destruction in the atmosphere. Once these parameters are found based on observations, they can be used to mathematically describe the changes in height, mass, velocity, and luminosity along the atmospheric trajectory [6,7]. Attention is given to adequately account for the actual atmospheric conditions at the concurrent time and location of a meteor. Lyytinen and Gritsevich [8] have recently proposed to tackle this problem by introducing atmospheric corrections into the model developed in [9]. Their approach can be inferred to produce more reliable estimates of the meteoroid's characteristic parameters and masses, since it uses an improved representation of the atmospheric density. In practice, these atmospheric corrections have already aided in a rapid recovery of the Annama meteorite based on the observations by the Finnish Fireball Network [8, 10, 11, 12, 13].

3. Summary and Conclusions

We analyze and compare the solutions obtained based on the analysis of the observed fireball events well-documented in the recent past. These events cover a representative sample of observational data, from meteorite-producing fireballs appearing annually, such as e.g. Annama, Košice, and Neuschwanstein to larger scale impactors, such as Chelyabinsk, Sikhote-Alin, and Tunguska. The comparison between these allows us to sum up the key features which are characteristic for each considered 'fireball group'.

From a wider perspective, we demonstrate the suitability of the proposed impact-classification scheme as a cornerstone of an advanced future model capable to robustly forecast consequences of meteoroids' interaction with the Earth's atmosphere and surface prior to their actual impact with the ground.

Acknowledgements

The ERC Advanced Grant No. 320773, the RFBR project nos. 16-05-00004, 16-07-01072, and 18-08-00074, and the Natural Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellowship program are acknowledged for supporting, in part, this project.

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EPSC Abstracts
Vol. 12, EPSC2018-976, 2018
European Planetary Science Congress 2018
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Computing mass indices of meteor showers with BRAMS data

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Abstract

We provide details about how to compute the mass index of the main meteor showers using data from the BRAMS network. We discuss the current limitations as well as the future solutions to overcome them. An example of application is provided with the Quadrantids 2016.

1. The BRAMS network

BRAMS (Belgian RAdio Meteor Stations) is a Belgian radio network using forward scatter reflections of radio waves on ionized meteor trails to detect and study meteoroids. BRAMS has been developed by the Royal Belgian Institute of Space Aeronomy since 2010 and consists of a dedicated transmitter and 26 identical receiving stations spread across Belgium. A short description of the BRAMS network and data will be provided.

2. Computing mass indices of meteor showers from BRAMS data

The mass index of a meteor shower can be obtained by fitting the slope of its cumulative mass distribution in a log-log plot. With radio observations, the maximum amplitude of meteor echoes is used as a proxy of the mass and the slope is fitted in the region of the graph dominated by underdense meteor echoes. The slope can be measured in a robust way using the Maximum Likelihood estimator. As an example of application of the method to BRAMS data, results for the Quadrantids 2016 will be presented for the period from 1st to 6th of January 2016.

A difficulty with the BRAMS data is that some meteor echoes can present an overlap in the frequency range with other signals coming either from the direct signal of the transmitter or from reflections on airplanes or both. In this case, it is harder to determine the maximum amplitude of meteor echoes. The strategies adopted to solve these issues will be presented.

The cumulative mass index will be estimated for the sporadic background using data from 1st and 2nd of January on one hand, and from 5th and 6th of January on the other hand. For the meteor shower, data from 3rd and 4th of January will be used.

Currently individual meteor trajectories are not yet available from BRAMS data. Hence, the position of the specular reflection points for underdense meteor echoes is not known and neither is the total distance traveled by the radio wave. We will discuss about this limitation and how this might affect the results.

EPSC Abstracts
Vol. 12, EPSC2018-979, 2018
European Planetary Science Congress 2018
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The Perseids: Results from 7 years of observations with the SPOSH camera

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Abstract

We will provide a full characterisation of the Perseid meteoroid stream using meteor observations acquired between 2009-2016 by the SPOSH camera systems. The image data will be reduced using a sophisticated software package developed to exploit the high performance of the imager.

1. Introduction

The Perseids is one of the most prominent meteor showers which can be observed from the Northern hemisphere. The stream is formed from accumulating dust particles originating from comet 109P/Swift-Tuttle. The Earth reaches the core of the stream particles around the 12^{th} of August each year when more than 100 meteors per hour can be seen visually under favorable observing conditions. Although, a high number of Perseid meteors is expected every year, variations in meteor activity do occur when freshly ejected material -usually a few revolutions old- intersects Earth's orbital path. Meteor observations during exceptionally high meteor rates are of great interest, since they hold important information regarding the stream formation and the evolution of the comet.

2. Method

2.1 The SPOSH camera

The SPOSH camera was designed to image faint short-lived phenomena, such as meteors or impact flashes on dark planetary hemispheres from an orbiting platform [4]. The camera is equipped with a highly sensitive back-illuminated 1024×1024 CCD chip and has a custom-made optical system of high light-gathering power with a wide field of view of 120×120°. For the determination of the meteor velocity, a mechanically rotating shutter with a known frequency is mounted in front of the camera lens. The shutter consists of two rotating blades and has a frequency of 250 rpm resulting in an exposure time of 0.06 sec for every shutter opening. Due to the camera's all-sky coverage and excellent radiometric and geometric properties, a large number of meteors can be obtained for reliable event statistics.

2.2 Observing campaigns

We have been monitoring the Perseid meteor activity every year since 2009 by operating a set of two SPOSH cameras in southern Greece. The observing stations were deployed in remote areas at altitudes of 1400-1600m above sea level ensuring ideal observing conditions during the night. The observations cover a time period starting from late July (λs $\sim$120) to mid-August (λs $\sim$145) covering the pre-maximum as well as post-maximum activity of the shower. While our principal aim is to monitor recurrent annual shower activity, we also observed significantly enhanced Perseid meteor rates in 2009 and in 2016, in agreement with predictions of the arrival of Perseid grains ejected at 1862, 1479, 1079 and 441 (Vaubaillon, in [2]; [3]). Overall, we estimate that several thousand Perseids have been recorded by our observing setup, not including meteors belonging to other showers that are active during the same period.

2.3 Data reduction

A sophisticated data processing pipeline has been developed to reduce the meteor image data acquired by the SPOSH camera system. The meteor detection algorithm is based on the Hough Transform technique for extracting linear features in images. The inner and outer orientation of the camera is determined by using the known positions of the stars depicted in the images. On a clear sky, the camera typically captures > 2000 stars on each frame. The reconstruction of the meteor trajectory is performed using the plane-line intersection method. The meteor speed is determined in a two-step process: first, the image is normalized for distance and aspect angle so as to create a new image of the meteor as it would appear if it was travelling parallel to the ground and passing through the local zenith point of each station. A search algorithm compares this image to a pre-computed database of synthetic images with the same geometry travelling at different speeds. The extraction of the meteor lightcurve is performed by applying a technique developed specifically for SPOSH image data [1]. It employs time-domain deconvolution to increase the temporal resolution in meteor lightcurves recorded simultaneously by two SPOSH cameras. Photometric calibration of the images is performed providing the correction parameters which will be applied on the measured instrumental magnitudes of the meteors. The software package has been validated using synthetic images, generated for a certain observing geometry, radiant, speed and brightness. These synthetic images were then used as input to the software package and the resulting meteor properties were compared against the given values.

3. Results

The data acquired during the observing campaigns will be processed using software developed at the Technische Universität Berlin (TUB) and the German Aerospace Center (DLR). A classification algorithm based on the meteor's radiant position, speed, time of occurrence and orbital elements will be applied in order to identify meteors belonging to the Perseid meteoroid stream. Other meteors will also be analysed searching for meteor showers active at the time of the observations. Flux estimates of the Perseid stream will be obtained by applying corrections accounting for the camera's observing area, radiant position and geometry between camera, meteors and radiant for certain time intervals. Magnitude population indices will be determined as a function of time by using the photometric properties of each Perseid meteor.

4. Summary and Conclusions

We have developed a software package for the reduction of meteor image data acquired by the SPOSH cameras. The precision and accuracy of the software package was verified with the help of simulated meteor images. We will provide a full characterisation of the Perseid meteoroid stream based on the large dataset acquired by the SPOSH cameras during the observing campaigns. Predicted outbursts for the Perseids from theoretical models will be compared against the observations and thoroughly investigated. We will investigate the association between sub-families identified within the Perseid meteoroid stream and different perihelion passages of the parent comet with the help of existing dust models.

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EPSC Abstracts
Vol. 12, EPSC2018-1062, 2018
European Planetary Science Congress 2018
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A spectroscopy pipeline for the CILBO meteor detection system

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Meteor spectra provide valuable information on the chemical properties of individual meteoroids [16, 1, 2, 17, 13, 11]. In some cases, this may be the only information on the chemical composition of the parent bodies, and on transforming processes that occur during the meteoroid's journey from its source to Earth. The CILBO spectroscopic program has been created with the intention of carrying out regular systematic spectroscopic observations. At the same time, the meteoroid trajectory and pre-atmospheric orbit are independently measured from data collected by the other cameras in the network. We will introduce and demonstrate the capability of the meteor spectroscopy pipeline developed by the Meteor Research Group of the European Space Agency and its application to the spectroscopic survey of meteors observed by CILBO, particularly the Geminid meteor shower.

1. CILBO meteor detection system

The Meteor Research Group (MRG) of the European Space Agency operates the double-station meteor camera system CILBO (Canary Island Long-Baseline Observatory). Currently, five image-intensified video cameras observe the night sky every clear night. Since full operations in 2012 [7] about 70 000 meteors have been observed. With two of the cameras (ICC7 and ICC9, set up on Tenerife and La Palma, respectively), we have recorded almost 20000 double-station meteors [5]. The recently installed large field-of-view cameras (LIC1 and LIC2) typically record between 1300 and 1700 meteors per month. The 3D trajectory and heliocentric orbits of these meteoroids were computed, and stored in the Virtual Meteor Observatory (VMO), which is the long-term archive of the International Meteor Organisation's video meteor camera network [6, 8]. Meteor orbits are computed using the MOTS code (Meteor Orbit and Trajectory Software) [4]. In the last years, the system was upgraded to include the recording of meteor spectra [3], operating image-intensified camera with objective grating (ICC8).

2. Meteor Spectroscopy Pipeline

The spectroscopy pipeline is divided into three steps. In the first step, cases with visible meteor spectra are selected. The second step is to retrieve the meteor spectrum from the raw images. Finally, in the last step, the meteor spectrum is analysed and modelled.

In the first step we preselect events that are used in the following analysis. For this purpose we use the MEteor Spectra Selector (MESS) software that goes over the ICC7 data mapping matching events in ICC8 data. At this stage, meteors with apparent magnitude lower than +3 are excluded, as meteor spectra for those cases are not detected by ICC8. The magnitude information is provided by `*.inf` files generated by MetRec [14] for events detected by ICC7. Moreover, from the same file, the pipeline software reads the pixel coordinates of the meteor that later are used to compute the expected spectral position in frames of ICC8. We analyse a box around the calculated position, where the signal-to-noise ratio and the absolute difference of intensity is computed. MESS creates the reference background image as median of 6 frames without meteor that MetRec additionally stores.

In the second stage, VIdeo Data Archiving System (VIDAS) [18] is used to perform the radiometric calibration by applying the dark current and flat field correction to each of the frames. The `*.inf` file of ICC7 contains for each frame the sky coordinates of the meteor (right ascension, declination). From this (RA, DEC) pair of ICC7, VIDAS computes the (RA, DEC) pair of each frame and each wavelength between 400 nm and 800 nm in steps of 0.5 nm. The (RA, DEC, wavelength) triple for each frame is then processed into a (x, y, wavelength) triple in the image coordinates. The spectrum is then computed by collecting for each frame from 400 nm to 800 nm the pixel value indicated by the (x, y, wavelength) triple.

At the last stage, the meteor spectrum is modelled using PARADE database (ESA's PlasmA RAdiation DatabasE) that undertakes a detailed assessment of the chemical species represented by each spectra. PARADE has been under development for several years [15, 12, 9]. It calculates the energy state transitions in atoms and molecules and the resulting emission. Originally developed for the purpose of the simulation of atmospheric entry plasma radiation in the atmospheres of Solar System planets and moons, it has been gradually expanded to include atoms and molecules measured in meteoroids [10]. Together with components of the air (O, N, N_2) the following elements are already implemented: Na, Mg, Fe, Ca, Cr, C, K, T, V, Mn, Ni, Co, Li, AlO, and TiO. A future update of the database will include more molecules, in particular FeO, MgO and CaO.

Acknowledgements

We acknowledge funding support from the faculty of ESA's Science Support Office.

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EPSC Abstracts
Vol. 12, EPSC2018-1093, 2018
European Planetary Science Congress 2018
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Russian fireball network for meteorite recovery and meteor observations

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A systematic search for meteorites with a minimum degree of weathering and known trajectory has become possible in the recent decades because inexpensive digital CMOS and CCD cameras appeared on the market [1, 2]. Fireball observation helps to determine the fall area quite correctly. Creation of the Russian fireball network in the Ural Federal University was officially announced in early 2016 [3]. There are two types of network stations in the proposed design of the fireball network: "professional" and "amateur".

Professional stations are to be located on the territory of educational or scientific organizations. These stations require separate buildings, stationary computers, high-quality digital cameras and fast and stable Internet connection. City buildings or astronomical observatories are good locations for the stations.

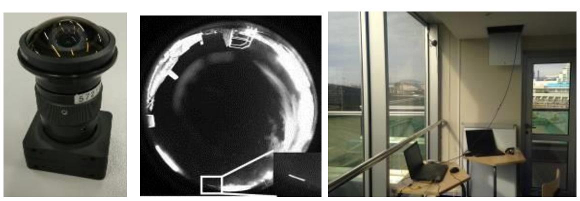

Figure 1: Chameleon3 CM3-U3-50S5M camera with Tokina TC1514HD-IR eye-fish objective mounted in the Sirius educational center February 2017, night sky view (landing airplane track is visible) and internal view of the room.

The Kourovskaya Astronomical Observatory, the Sirius Educational Center and the Crimean Astrophysical Observatory were selected to host the professional stations for the first time (Fig.1,2).

Amateur stations (Fig.3) are inexpensive, lightweight, located within 200 km of the main (professional) station and are served by amateur astronomers.

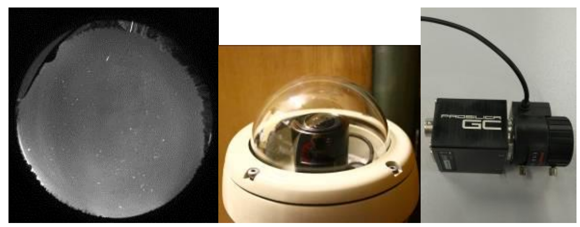

Figure 2: Bright meteor on night sky registered by all-sky camera installed in Kourovska observatory (Middle Ural) and view of Prosilica GC 1380 camera with objective.

Installation of fully automatic stations in Russia is not feasible due to the cold climate, high annual precipitation, insufficient illumination for solar cells and absence of the good Internet connection. In addition, the search for the meteorites in the remote locations, especially in the northern parts of the Russia, is difficult due to the lack of settlements and transport infrastructure there, even if the fall area was determined precisely enough.

Figure 3: Internal and external view of Amateur station (QHY5LIIM camera and Computar 1.8-3.6mm 1.6 lens) operated by Raspberry Pi 2 Model B Rev 1.1. installed in Crimean observatory. It has 7m limiting magnitude and 110-degree field of view.

In addition to the data from the stations, photos and videos provided by eyewitnesses are still used to analyze the trajectory. This allowed us to develop the network with minimal costs and in a short time.

In 2017, a specialized cloud service was created to gather and store data coming from cameras. The service had eased the task of data gathering, but the increased amount of the incoming data had led to a new task of the automatic fireball detection. The detection must occur on a client side in order to avoid the server overload. Therefore, the development and implementation of the appropriate detection algorithms had started. Now, we are developing adaptive self-learning algorithms. Considerable attention is being paid to the portability of the algorithms to different platforms, which will allow anyone to use the solution. We had also started developing a method for calculating fireball trajectories [4]. We use other objects (e.g. satellites, planes, meteors) to calibrate the method. This time, we are able to determine a fall area of a fireball within a day

Figure 4: Bright fireball 06.03.2018 (white circle) over the Katajsk city and meteor shower registered by the Irbit station (Middle Ural) last winter.

Due to the wide network coverage, we regularly receive information about events and eyewitnesses' footages. During the last two years, we detected a dozen fireballs that might have reached the Earth surface and calculated trajectories for all of them. Unfortunately, most of these fireballs were observed over the locations difficult to reach (e. g. taiga, marsh, remote areas). Nevertheless, one of the recent events was registered on March 6, 2018 at 22:58 local time near the city of Kataysk [5], which is quite convenient for searching. At the moment, the search expedition exploring the possible fall area. The fireball was registered by the All-sky camera of the Ural segment of the network, at the station located in the Irbit city. The detection allowed us to quickly calculate the fireball trajectory and send an expedition to the area. Eyewitnesses' evidence confirmed the correct choice of the search area and, thus, it can be argued that the Russian fireball network is actively functioning (Fig.5).

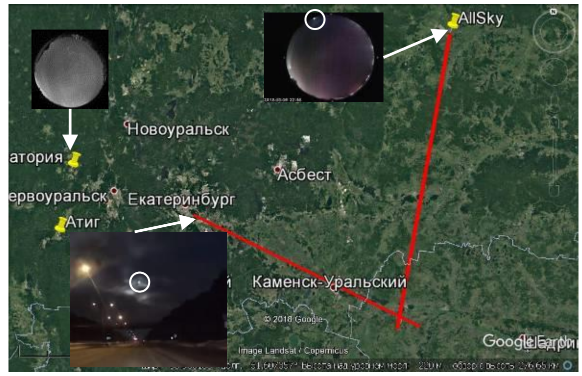

Figure 5. Map generated with Google Earth for Katajsk event (white circle). Yellow marks demonstrates positions of fireball network stations in Ural segment. Red lines are directions for eyewitnesses' video (insertion) and Irbit station all-sky camera.

Acknowledgements

This work was supported by Act 211 of the Russian Federation, contract N02. AO321.00006 and the PROTOPLANETS Project. (K.N.A.) by State Task of the FASO of RF (Theme "Pressure" № AAAA-A18-118020190104-3).

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EPSC Abstracts
Vol. 12, EPSC2018-1105, 2018
European Planetary Science Congress 2018
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FRIPON and IMPACT projects to pinpoint interplanetary matter in the centimetre - hundred meter range

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Abstract

Improving our knowledge of the interplanetary matter is important to better understand the evolution of the solar system. However, it is mostly undetectable except when it enters the terrestrial atmosphere or when it is large enough to be detected by optical telescopes [1] (Harris et al, 2015). There is in particular a lack of knowledge for particles between 100 m (exhaustive limit of large telescopic surveys) and a few centimeters (typical maximum size for meteor surveys) (fig 2). Fireball observation networks like FRIPON (Fireball Recovery and Interplanetary Observation Network) [2] (Colas et al, 2014) can fill this gap for objects between a few centimeters and a few meters. For larger objects, fall statistics on Earth are too low to determine a precise impact flow. The idea of the IMPACT project is to detect the similar falls of objects from several meters to a hundred meters on Jupiter and Saturn: such events should be more frequent on these more massive planets than on the Earth [3] (Delcroix et al 2015).

1. FRIPON project

The aim of the FRIPON project is to better constrain the connections between meteorites and asteroids. It is easy to study a meteorite in the laboratory but we cannot tell where it came from, because its orbit is most of the time unknown. On the other hand, we currently have more than 750,000 asteroid orbits with almost no physical information. However, these parameters are crucial for understanding the origin and evolution of the solar system.

The goal of the FRIPON network is to detect large objects that are possible sources of meteorites. We decided to use fisheye cameras to detect fireballs of negative magnitude, allowing us to detect particles larger than a few millimeters. To reach a sufficient statistic we decided to cover the entire French territory (fig 1). We measure an average of 2000 orbits a year and expect to get one meteorite a year.

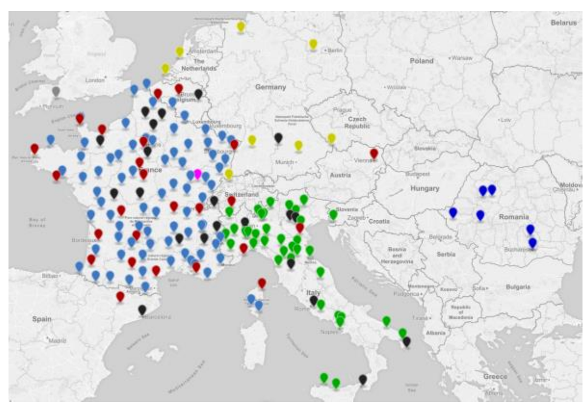

Figure 1*: State of the FRIPON network (95 cameras installed, light blue) and extensions in Europe, PRISMA (Italy, green), MOROI (Romania, dark blue). Red dots are for radio stations using GRAVES radar*, black for station in installation, yellow for new European networks.

2. IMPACT project

The size distribution of dust and asteroids are known with relative accuracy only in the immediate vicinity of the Earth (fig 2). It is essential to model this flow precisely to understand the formation of the Solar System, in particular to measure the age of planetary surfaces determined by crater counting. The IMPACT project aims to monitoring the surfaces of giant planets with the best temporal continuity to obtain a good statistic of these impacts. It proposes to coordinate observation campaigns with the 1 meter telescope of the Pic du Midi Observatory by associating amateur and professional astronomers in order to maximize the temporal coverage of the observations.

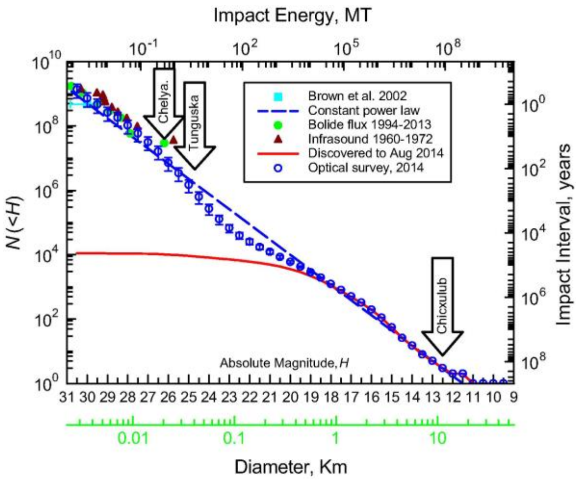

Figure 2 : *Cumulative distribution of Near Earth Asteroids [1](Harris and D'Abramo, 2015)*

The IMPACT program is complementary to the one carried out by the University of Bilbao, in particular with the development of the DeTeCt program [3] (Delcroix et al, 2013), aiming to automatically detect possible impact flashes in the observations of Jupiter routinely performed by amateur astronomers.

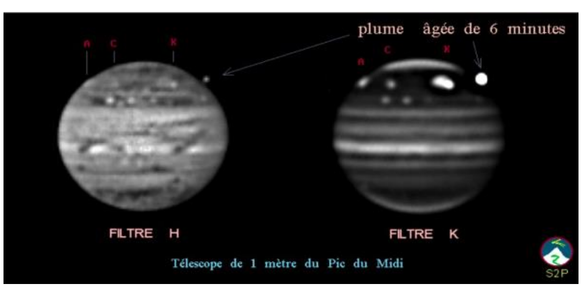

Figure 3 : *Impacts of SL9 comet on Jupiter. On the right image, made with CH4 narrow band filter, it is possible to see (top) the flash and traces of older impacts at the same latitude [4] (Colas et al, 1995).*

IMPACT will not only detect live flashes, it will be especially focused on the detection of impact traces with lifetimes of a few days to several months, such as the impact of comet SL9 in 1994 (fig 3). Our goal is to observe Jupiter twice a month, and thus exhaustively detect all traces that last a few weeks or more. With the image quality of the 1m Pic du Midi telescope, we can detect objects from ten meters to a hundred meters. Beyond this size, Jupiter events will be too rare to measure an impact flux with a good precision.

3. Conclusion

With the combination of the FRIPON and IMPACT programs, we hope to be able to measure the flow of inter-planetary material at the Earth's orbit as well as for Jupiter and Saturn, and obtain a new a global model for the whole Solar System. With the addition of meteor observations and the discovery of near-Earth asteroids, we will thus have a global assessment of the matter falling on Earth from a few 1/100 mm to 1000 km. The knowledge of this flow will also yield better estimates of the age of cratered surfaces outside those of the Moon that have been calibrated with sample returns.

Acknowledgements

The FRIPON project is funded by the French ANR (Agence Nationale de la Recherche: www.anr.fr).

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EPSC Abstracts
Vol. 12, EPSC2018-1154-4, 2018
European Planetary Science Congress 2018
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Observations of the 3200 Phaethon and Geminid meteor shower during the epoch of close approach with the Earth

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Abstract

Results of the coordinated observations of the asteroid 3200 Phaethon and Geminids meteor shower during the epoch of close approach with the Earth (16 December 2017) are presented.

1. Introduction

In December 2017, the asteroid (3200) Phaethon approached to the Earth at a distance of 0.069 AU, the smallest in the interval 1983 (discovery) – 2093 (approaching 0.02 AU). Since its discovery in 1983 and until 2009, the asteroid has shown no activity, although its search was conducted. In 2009, observations from the NASA STEREO space observatory made it possible to record a short-term (about two days) activity in perihelion [1]. This phenomenon was also observed in 2012 and 2016 [2, 3].

Asteroid Phaethon is the parent body of a main annual meteor shower of Geminids, which is observed on Earth in the middle of December. Mathematical simulation [4] showed that the structure of Geminids is consistent with the comet scheme of its formation. However its origin is still under discussion. E.g. a dynamical pathway was found from the Pallas family [5, 6], but how the Geminids could be generated on this pathway is not clear. We need more data allowing to ascertain physical properties of the asteroid, so we need more observations.

Results of mathematical modeling [7] has shown that activity of the Geminid meteor shower should rise with time, and that was confirmed by analysis of visual observations 1985–2017 [8]. We need more data of the shower observations, especially its flux density and meteoroid mass distribution profiles.

2. Observations and results

The observations of the asteroid (3200) Phaethon and the Geminid meteor shower were carried out in epoch of close approach of the asteroid with the Earth.

We observed asteroid (3200) Phaethon at the prime focus of the 2-m telescope Terskol branch of INASAN (Russia) and 1.3-m telescope Skalnaté pleso (Slovakia). We conducted a long series of photometric observations aimed to infer the light curve of Phaethon. These data allow us to investigate the physical characteristic of the object.

The observations of the Geminid meteor shower were performed from the territory of Cuba (the reserve “Sierro del Rosario” (~70 km from Havana)). The wild-field of view camera Watec LCL-902H3 and the lenses Computar F=2.9–8.2 mm were used for observations. The results of observations of meteors during the period 12–14 December 2017 (in period of Geminid meteor shower maximum activity) are presented.

Using these data we estimated of the variation of activity of the Geminids (ZHR and IMA) in 2017 and compare with the different visual and television data. According to the various data and mathematical simulation [7, 8] the activity of Geminids in 2017 was increased.

3. Summary

The coordinated observations of the asteroid 3200 Phaethon and Geminids meteor shower in 2017 to allow us to estimate the physical characteristic of the asteroid (color, radius and period rotation) and characteristics of the Geminid meteor particles.

Acknowledgements

AK acknowledges support from the Program № 28 of the fundamental research of the Presidium of RAS and the RFBR grant № 16-02-00805-a. OI is supported, in part, by the project 16BF023-02 of the Taras Shevchenko National University of Kyiv, the SASPRO Program, REA grant agreement No. 609427, and the Slovak Academy of Sciences (grant Vega 2/32/14). RGO was supported by grant (N 8.2.12.2018) from `The Tomsk State University competitiveness improvement programme'.

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EPSC Abstracts
Vol. 12, EPSC2018-1164, 2018
European Planetary Science Congress 2018
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Validation of the open-source software Meteor Toolkit

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Abstract

This study focuses on validation of the Meteor Toolkit – an open-source software for determining the meteoroid orbit based on meteor observations using the integration of differential equations of motion. In our recent work [2, 3], we have performed comparisons of the proposed technique with traditional methods and with the available results of meteoroid orbits calculated by the other authors. Here we validate Meteor Toolkit using the trajectory data of HAYABUSA space vehicle re-entry.

1. Introduction

It is known that the orbits of meteoroids that collide with Earth are exposed to significant perturbations prior to the encounter, these are primarily from the influence of gravity and atmospheric drag at the end of its trajectory. A standard method of meteoroid orbit computation [1] is traditionally based on a set of corrections applied to the observed velocity vector. In particular, the popular concept of 'zenith attraction' is used to correct the direction of the meteor's trajectory and its apparent velocity in the Earth's gravity field.

Progress beyond the state of the art: In the recent work we proposed other, more explicit approaches to orbit determination and to error propagation analysis [2, 3]. Our approach to meteor orbit determination is based on strict transformations of the coordinate and velocity vectors according to the IAU International Earth Rotation and Reference Systems Service (IERS) [4] and the backward numerical integration of differential equations of motion [5,6]. We have implemented this technique for the determination and analysis of meteoroid orbits into an open-source software entitled "Meteor Toolkit" [7].

2. The software

Free distributable open-source software Meteor Toolkit for determination and analysis of orbit of meteoroids was developed. This software is based on strict transformations of coordinate and velocity vectors according to the IAU International Earth Rotation and Reference Systems Service (IERS) [3] and backward numerical integration of differential equations of motion [4, 5]. The software has a graphics user interface and uses freely distributed routines and kernels from the SPICE system [8] for coordinate transformation and computing the ephemeris. The JPL ephemeris, DE421 [9], is used for transformation of the meteoroid's position and velocity vectors from a geocentric to a heliocentric coordinate system. The backward integration of equations of perturbed meteoroid motion:

$$\ddot{\vec{r}} = \frac{GM_{Sun}}{r^3}\vec{r} + \ddot{\vec{r}}_{Earth}(C_{nm}, S_{nm}, \vec{r}, t) + \ddot{\vec{r}}_{Moon}(\vec{r}, t) + \sum \ddot{\vec{r}}_{planets}(\vec{r}, t) + \ddot{\vec{r}}_{atm}(\vec{r}, t)$$

is performed by implicit single-sequence numerical methods [5-6]. The equations of perturbed meteoroid motion include central body (Sun) attraction, perturbations from Earth gravity field, Moon, other planets, and from atmospheric drag. To obtain an undistorted heliocentric orbit a backward integration is performed until the meteoroid intersects with the Hill sphere. The JPL Horizons On-Line Ephemeris System [10] database of comets and asteroids is then searched for the meteoroid's potential parent body. In addition, the software has a module for visualizing the computational results. In summary, "Meteor Toolkit" enables robust analysis of the orbital motions of meteoroids through time prior to Earth's capture, enables search for their potential parent bodies, as well as to obtain characteristic physical meteoroid parameters and calculate the location of meteorite's impact with the ground [11-14].

3. Observations and Control Data

HAYABUSA mission re-entry trajectory data is useful for validation of a software for orbit determination because from one side the event was well recorded by the fireball network cameras and from the other side the orbit of the HAYABUSA space vehicle before Earth's gravitational influence was determined with the help of radio technical trajectory measurements. Therefore it is possible to compare results of orbit determination based on different types of observation and obtained by different methods. In this research the position, height and velocity of the space vehicle and capsule at the corresponding time estimated by TV and photographic observations were taken from papers [15] and [16]. Azimuth and elevation of the velocity vector (radiant) were obtain by straight lines between points of HAYABUSA re-entry trajectories. Initial state vector of the HAYABUSA space vehicle obtained by JAXA in the Earth-Centered Inertial Equatorial Coordinate System J2000.0 [17] was transformed into heliocentric orbital elements relative to the ecliptic.

4. Results

The results of the HAYABUSA orbit determination, obtained with the help of the Meteor Toolkit from the photographic observations of the space vehicle and the capsule from the fireball networks, are presented in Tables 1 and 2, respectively. For comparison, the same tables give orbital elements computed from the HAYABUSA state vector after the final orbit correction. For both, the spacecraft and the capsule, the orbital elements obtained differ from the control ones within the influence of observation errors.

Table 1. Calculation of the orbit of the HAYABUSA space vehicle at 2010-06-09 UTC 06:04:00.0.

	Telemetry	*This study*
a, (AU)	1.32378	1.32335±0.0027
e	0.25730	0.25692±0.0015
$i°$	1.68396	1.68346±0.0162
$\Omega°$	82.46602	82.46656±0.0017
$\omega°$	147.47394	147.54737±0.3710
$M°$	16.07552	16.045887±0.3508

Table 2. Calculation of the orbit of the HAYABUSA capsule at 2010-06-09 UTC 06:04:00.0.

	Telemetry	*This study*
a, (AU)	1.32378	1.32312±0.0027
e	0.25730	0.25730±0.0015
$i°$	1.68396	1.64934±0.0162
$\Omega°$	82.46602	82.46570±0.0017
$\omega°$	147.47394	147.22083±0.3710
$M°$	16.07552	16.22785±0.3508

Acknowledgments

The authors are grateful to the developers of the freely distributed procedures and kernels of SPICE system [7] which are incorporated in Meteor Toolkit. The ERC Advanced Grant No. 320773, and the Russian Science Foundation project No. 14-22-00197 are acknowledged for supporting, in part, this work.

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EPSC Abstracts
Vol. 12, EPSC2018-1226, 2018
European Planetary Science Congress 2018
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Investigating Fireball Flight in Three Dimensions

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Abstract

Fireball trails recorded on long exposure, Desert Fireball Network images are encoded with a unique time sequence that is synchronised between systems to 0.4 ms. This allows triangulation of individual positions along a meteoroid path as it passes through the atmosphere. Using this technique on the >21 second long fireball caught by the DFN in 2015 shows a distinctly non-linear path. A 3D particle filter, using raw astrometric observations is best suited to characterise the meteoroid and its trajectory.

1. Introduction

Dedicated camera networks, such as the Desert Fireball Network in Australia (DFN), have been established to observe the fireball phenomenon associated with meteoroid entry through the atmosphere. Multi-station triangulation can recreate a meteoroid's path, facilitating orbit determination and meteorite recoveries. The DFN captures approximately one > 2 seconds fireball per night over its 3 million km^2 observing area. This exceptionally large collecting area, combined with the very high astrometric precision of the DFN instruments, allow us to look at a significant number of long and shallow meteoroid entries in great detail.

1.1 Calculating trajectories

Typical methods for triangulating meteoroid trajectories assume a straight line path, with deviations added for known phenomena such as gravity. The DFN captures long exposure images and the modulation of a liquid crystal shutter results in segmented fireball trails. The de Bruijn encoding used by the DFN embeds a unique, absolute time signature which is synchronised across the network via GNSS. This provides the unique capability of individually triangulating meteoroid positions for every time-step with multi-station observations. Performing this *pointwise* triangulation allows us to investigate the true movement of a meteoroid without imposing any assumptions on trajectory geometry and fireball dynamics.

1.2 Characterising meteoroids

Meteoroid characteristics such as mass and density are estimated by assessing deceleration profiles and light curves. This modelling is inherently linked to the triangulation solution. A particle filter, as applied by Sansom et al. (in review), is an iterative Monte Carlo technique that does not aim to fit the entire trajectory at once, rather it estimates the state (position, velocity, mass, density, etc.) at each observation time using a cloud of particles. Using this method with a three dimensional model allows the raw astrometric observations to weight particle fits. This removes the need for pre-triangulating the entire trajectory, eliminating the need for preconceived assumptions such as a straight line trajectory.

2 Investigating meteoroid data

The >21 second long fireball observed by the DFN in December 2015 is shown to not follow a straight line path. A 3D particle filter is well suited to analysing the characteristics of this meteoroid case. The entry radiant is also affected, changing the predicted heliocentric orbit noticeably.

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