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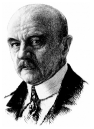

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THE CHALLENGES IN HYPERVELOCITY MICROPHYSICS RESEARCH ON METEOROID IMPACTS INTO THE ATMOSPHERE

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Abstract: Meteor science contributes greatly to the study of the Solar System and the Earth's atmosphere. However, despite its importance and very long history, meteor science still has a lot to explore in the domain of meteor plasma microphysics and the meteor–ionosphere interaction. Meteors are actually a difficult target for high-resolution observations, which leads to the need for more ambitious interdisciplinary observational setups and campaigns. We describe some recent developments in the physics of meteor flight and microphysics of meteor plasma and argue that meteor science should be fully integrated into the science cases of large astronomical facilities.

Keywords: meteors; impacts; hypervelocity; ionosphere; Solar System

Introduction

Meteoroids are objects populating the interplanetary space and have a size range from meters to small dust particles. Unlike planetary objects, meteoroids' orbits are strongly influenced by non-gravitational forces (e.g. Poynting-Robertson effect, radiation pressure, Yarkovsky effect, solar wind, etc.). The outcome of such orbits is the removal of meteoroids from the Solar System, whether by eventually reaching a hyperbolic trajectory out of the system or by collision with larger objects or by sublimation when they approach close enough to the Sun. Their collision with objects that have a dense atmosphere is actually happening with the atmosphere. The meteoroids enter the atmosphere with large hypersonic velocities (~11–72 km/s in case of the Earth, Gritsevich, 2009) that lead to high pressures and temperatures that ablate the meteoroid body. This fiery demise of a meteoroid particle is seen from a distance as a luminous phenomenon called a meteor.

Meteoroids collide with the Earth's atmosphere on a daily basis. On average, meteoroids cumulatively deposit about 5 to 300 tons of material per day (Plane, 2012; Silber, Boslough, Hocking, Gritsevich, & Whitaker, 2018), mostly into our atmosphere and only a tiny amount to the Earth's surface in a form of meteorite falls. Meteors have been an integral part of astronomy since ancient times as they are easily observed with the naked eye. Sometimes large meteors (called

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*Corresponding author, e-mail: dejan@iszd.hr fireballs) create very bright and impressive events, accompanied by sounds and meteorite falls. Hence, meteor astronomy is a very important part of the science popularization efforts. On top of that, large impacts can create damage on the ground and lead to injuries and death. For example, the Chelyabinsk meteor in 2013 exploded at about 20 km altitude and created extensive damage on the ground and injuries (Kartashova et al., 2018). This was a reminder that meteor study brings important knowledge about the space objects that pose a danger.

Meteors are relevant to a wide range of science branches. The material deposited by meteors plays a very important role in the physical and chemical processes happening in the atmosphere. For example, meteors deposit electrons and ions into the ionosphere (Pellinen-Wannberg, Häggström, Carrillo Sánchez, Plane, & Westman, 2014). A part of this material is in a form of tiny dust particles that contribute to the formation of noctilucent clouds (Hervig et al., 2012). Deposited material can also be of organic composition, which leads to the theories of space origin of chemical ingredients required for life formation on young Earth (Jenniskens, 2001). The problem is that the deposited material in all these examples undergoes changes during the energetic process of hypersonic meteor flight, powered by the kinetic energy due to the meteoroid’s high velocity.

Meteoroids originate mainly from asteroids and comets. This makes meteor physics an important contributor to our understanding of the Solar System. A small fraction of meteoroids has some other origin, such as ejecta from large asteroid impacts onto planets, their satellites, or they come from other planetary systems. These topics also bring importance to meteor astronomy. However, even though meteors can be easily seen, they are very difficult to be scrutinized with high resolution astronomical techniques. The problem is that meteors are brief, unpredictable transient events with a large angular size and a random spatial position in the sky. It is very difficult to focus high resolution sensors to such a large random event. Moreover, three different flow regimes (i.e., three different physical concepts) happen in the meteor plasma during a single meteor flight as the meteor penetrates into deeper layers of the atmosphere.

Since meteorites are remnants from the collisions of the extra-terrestrial bodies (and hence in many cases their parent bodies no longer exist in the Solar System in their original form), meteorite (fall) recovery is an exciting source of data and it is complementary or even a cheap analogue to the expensive sample return missions from the Solar System bodies. Meteor observations, their robust interpretation, and understanding which fireballs are dropping meteorites provide the necessary geospatial content on where in the Solar System we get what type of material from. This information is crucial to discriminate between different planetary system formation models. When ”observing a meteorite fall”, the link is missing from the picture, meteorites can be compared to more distant planetary objects based on their reflectance spectra (Martikainen, Penttilä, Gritsevich, Lindqvist, & Muinonen, 2018; Penttilä, Martikainen, Gritsevich, & Muinonen, 2018), however this match currently provides less confidence compared to the exact orbital dynamics (Dmitriev, Lupovka, & Gritsevich, 2015; Meier et al., 2017; Trigo-Rodríguez et al., 2015). It is also better to recover fresh meteorites that have not gone through the process of alternation by weathering (Li et al., 2019), which makes meteor flight reconstruction an imperative.

Thanks to the technological advancements in sensors and observational instruments (telescopes, radars, infrasound, etc.) in recent years, meteor astronomy has been gaining in the quality, quantity and diversity of meteor data. This trend is increasing as even more ambitious instruments are about to become operational, which created a new level of problems related to the challenges of Big Data approach to the data analysis (Vinković et al., 2016). Advancements in the last two decades have already produced a number of meteor observations that lack a clear explanation. The key reason for these gaps in our understanding of the meteor-related phenomena is the complexity of the meteor plasma microphysics under extreme hypersonic flight conditions. The complexity includes partially charged meteor plasma that undergoes complex chemical and physical changes under hypersonic shock, exposed to the Earth's magnetic field and ram pressures of the incoming atmosphere from very low values to extremes that can disintegrate the meteoroid at the meteor core. Here we will discuss some examples of such discoveries and theoretical attempts to bring new insights into the physical processes happening in the meteor plasma.

The physics of meteor flight

Meteor phenomena start at altitudes where the atmosphere is of an extremely low density (Gritsevich & Stulov, 2006). The very first interaction between this atmosphere and a meteoroid is through direct high speed collisions of atmospheric molecules with the meteoroid body. These collisions sputter particles out of the meteoroid surface, which then thermalize through further collisions in the atmosphere. This part of the meteor flight is called "free molecular regime" flow. As the meteor penetrates deeper into the atmosphere, the flow regimes, and the physics that describes them, change.

The flows regimes can be distinguished by dimensionless numbers such as the Knudsen number $\mathrm{Kn} = \lambda/L$ or the Reynolds number $\mathrm{Re} = \rho v L/\mu$, where λ is the mean free path of the gas molecules, L is the characteristic length scale of the body, ρ is the gas density, v is the flow (i.e., meteoroid) speed, and μ is the gas-dynamic viscosity. The flow regimes can be defined as the following (Moreno-Ibáñez, Silber, Gritsevich, & Trigo-Rodríguez, 2018):

- Free molecular regime: $\mathrm{Kn} > 10$
  Flow properties: The number of intermolecular collisions is scarce. Single molecules hit the immersed body.
- Transitional-flow regime: $0.1 < \mathrm{Kn} < 10$ or $\mathrm{Re}^{-1/2} < \mathrm{Kn} < 10$
  Flow properties: The mean free path of the molecules is of the same order of magnitude as the characteristic size of the body. There are collisions between molecules. The vapour cloud is formed.
- Slip-flow regime: $0.01 < \mathrm{Kn} < 0.1$ or $0.01\,\mathrm{Re}^{-1/2} < \mathrm{Kn} < \mathrm{Re}^{-1/2}$
  Flow properties: There is a slightly tangential component of the flow velocity in the boundaries of the body's surface, but there is no adhesion of the flow to the body's surface.
- Continuum-flow regime: $\mathrm{Kn} < 0.01$ or $\mathrm{Kn} < 0.01\,\mathrm{Re}^{-1/2}$
  Flow properties: The flow is considered to be continuous.

The complexity of modelling meteor phenomena often lies in the necessity to assume a range of input parameters (such as shape, size, bulk density, porosity, and also the way they change with time) which in turn would allow to discriminate between the flow regimes and operate at each stage of meteor flight with the "right" set of equations describing meteor physics. Such approach may be misleading in interpreting meteor observations because artificial initial assumptions may rule out the actual (real) scenario from the very beginning.

This difficulty can be overcome by retrieving a self-similar solution, i.e., finding a solution in a form which is similar to itself if the independent and dependent variables are appropriately scaled (for detailed description see e.g., Barenblatt, 1996). Such realization based on analytical solution of meteor physics equations was proposed by Gritsevich (2007, 2008a). According to this solution, two self-similarity parameters, α and β, can be uniquely identified for any meteor event based on the observed rate of deceleration and mass loss in the atmosphere. The advantage of using this dynamical model is that it does not require any prior assumption about the meteoroid. Also, it does not require any data on meteor brightness. The interpretation of the light curve, or so-called photometry, can be subsequently done based on already resolved flight dynamics and it would additionally allow to retrieve the shape change coefficient μ (Bouquet et al., 2014; Gritsevich & Koschny, 2011). Hence, the dynamics of meteor flight can be efficiently parameterized with the following dimensionless parameters:

- The ballistic coefficient $\alpha = \frac{1}{2} c_d \frac{\rho_0 h_0 S_e}{M_e \sin\gamma}$ characterizes the aerobraking efficiency, since it is proportional to the ratio of the mass of the atmospheric column along the trajectory (with the cross section S_e) to the body's pre-atmospheric mass,
- The mass loss parameter $\beta = \frac{1}{2}(1-\mu)\frac{c_h V_e^2}{c_d H^*}$ is proportional to the ratio of the fraction of the kinetic energy of the unit body's mass to the effective destruction enthalpy,
- The shape change coefficient $\frac{S}{S_e} = (\frac{M}{M_e})^{\mu}$ characterizes the possible role of the meteoroid rotation in the course of the flight and hence may intensify mass loss.

Here M is meteoroid mass, V is velocity, S is the cross-sectional area of the body, γ is the local angle between the trajectory and the horizon, H^* is the effective enthalpy of destruction, c_h is the heat-transfer coefficient, c_d is drag coefficient, h_0 is the height of the homogeneous atmosphere, ρ_0 is the atmospheric density at sea level, and the subscript e indicates the parameters at the entry into the atmosphere.

An elegant way of solving α and β was recently described by Lyytinen and Gritsevich (2016). Their study details an "easy switch" to the desired atmospheric model in processing the observational data so that it extends the applicability of using the analytical model beyond the exponential atmosphere model (which naturally allows for analytical representation). One option for handling large meteor datasets is integrating the MSISE atmospheric model (Community Coordinated Modeling Center, n.d.) that describes the neutral temperature and densities in the atmosphere from ground to thermospheric heights. At the heights below 72.5 km the MSISE model was primarily based on tabulation of zonal average temperature and pressure (Barnett & Corney, 1985). The model was supplemented by historical rocket and incoherent scatter data in the upper mesosphere and lower thermosphere. Low-order spherical harmonics and Fourier series were used to describe the major variations throughout the atmosphere including latitude, annual, semiannual, and simplified local time and longitude variations (Hedin, 1991).

However, since in certain circumstances the true isobaric level may be considerably off the heights predicted by the established atmospheric models (due to, for example, extreme weather conditions, winter, locations over high latitude regions), processing of some fireball cases requires more careful considerations (Lyytinen & Gritsevich, 2016). Hence, the real atmospheric data from national weather services can be also fitted into the model. Lyytinen and Gritsevich (2016) detail examples of using the Global Forecast System (GFS) data and the data from the European Centre for Medium-Range Weather Forecasts (ECMWF) capable to assist modelling of meteor flight with unprecedented level of match to the actual (real) atmospheric conditions.

The concepts explained in this section help understanding the meteor phenomena and have diverse scientific applications. Examples of such applications include:

- determination which fireballs are likely meteorite drop candidates (Gritsevich, Stulov, & Turchak, 2012; Sansom et al., 2019; Turchak & Gritsevich, 2014),

- actual meteorite recovery based on drop predictions (Kohout et al., 2017; Maksimova et al., 2020; Trigo-Rodríguez et al., 2015),
- further grouping of events according to specific values of α and β, e.g. criterion for impact crater production (Gritsevich, Stulov, & Turchak, 2013),
- explanation of consequences observed in even more unique historical cases, such as Tunguska event in Russia on 30 June 1908 (Gritsevich, Stulov, & Turchak, 2012; Stulov, 1998),
- terminal height prediction (Moreno-Ibáñez, Gritsevich, & Trigo-Rodríguez, 2015),
- cross-validation with various techniques (Gritsevich, 2008b, 2008c), e.g., pre-atmospheric size/mass estimates obtained using the ballistic coefficient α agree well with the estimates derived from the cosmogenic radionuclide activities measured in the laboratory (Gritsevich et al., 2017; Kohout et al., 2017; Meier et al., 2017),
- detectability of meteors, e.g., simulation of the capabilities of a camera onboard the ISS (Bouquet et al., 2014),
- efficient grouping and handling in large meteor datasets (Sansom et al., 2019).

Microphysics of meteor plasma

Our understanding of meteor plasma and hypervelocity shock physics in rarefied partially ionized and partially magnetized ionospheric plasma is not complete. We still lack a detailed breakdown of all microphysical components of a meteor and how it interacts with the surrounding ionosphere. Problems start with the very first interactions between the meteoroid body and the atmosphere. The free molecular regime flight was considered as a non-luminous process. In other words, the meteors were typically detected at altitudes below 130 km, when the transitional flow regime starts and produces enough light to be seen from the ground.

It was about 20 years ago that the first high altitude meteors (i.e., meteors above 130 km altitude) were detected (Spurný, Hans, Jobse, Koten, & Leven, 2000). The source of the emitted light was a mystery until the modelling showed that particles sputtered from the meteoroid surface travel at such a high speed relative to the surrounding atmosphere that they undergo many collisions before slowing down to the local average speed of atmospheric molecules (Vinković, 2007). The collisions excite molecules that then emit light and, since the molecular mean free path is large at these altitudes, the images of high-altitude meteors typically show a large coma around the central object. This coma becomes smaller as the meteor travels deeper into the atmosphere because the mean free path is decreasing. No significant improvements of this model have been explored since then. We know that some of the collisions must be energetic enough to create ionization and free electrons. Above 130 km, both the ions and electrons are trapped into gyration by the Earth's magnetic field, thus the behaviour of such partially ionized plasma is expected to be non-trivial. The chemistry of the high-altitude meteor coma is also unexplored. Moreover, observations with a high-power, large-aperture radar (49.92 MHz) (Gao & Mathews, 2015) detected events (i.e., meteor plasma dynamics) in high-altitude meteors that lack explanation (they call it the "dragon" events).

At altitudes of about 120–130 km (depending on the meteoroid size) a vapour cloud around the meteoroid emerges and this vapour now takes on itself the first collisions with the incoming atmospheric molecules. This is a transitional-flow regime and we still lack a detailed microphysical model of it. We have a rough sketch of the concept as we know from observations that this type of flow should exist (Popova, Sidneva, Shuvalov, & Strelkov, 2000). The vapour cloud quickly evolves a shock front that separates the low-density, high-speed incoming atmosphere and the high-density, slow-speed flow round the meteoroid body. The meteor then quickly evolves into a structure typical for hypersonic flows under higher atmospheric densities.

When the hypersonic flow is achieved, the meteor enters the slip-flow regime. Silber, Hocking, Niculescu, Gritsevich, and Silber (2017) describe how such a meteor should look like based on the current understanding of the physics of hypersonic flight. When the meteor enters a dense enough atmosphere (the exact altitude depends on the meteoroid size, but typically this should be applicable as high as 100–120 km) a bow shock wave front forms that engulfs the entire meteor. At the top of the front is the "ballistic" shock front, which is the place where the first collisions with the incoming atmospheric particles happen. Behind the ballistic shock is the sonic region that travels with the meteoroid and flows around the body with subsonic speeds. The meteoroid body is covered by a boundary layer that does not stick to the solid meteoroid surface. The surface is melting and evaporating, with the products entering the flow and being carried away behind the meteoroid body into the wake. A turbulent flow appears immediately behind the meteoroid. At some distance from the meteoroid, the flow is compressed into a small "neck" behind which the gas recompresses through adiabatic expansion, leaving a turbulent vapour trail.

The heat of compressed gas melts the body, which leads to several scenarios of its final destruction. The first possibility is that the melting persists smoothly all the way until the entire body melts and evaporates. The second possibility is that the body has various inhomogeneities where some parts melt or evaporate much faster than the rest of the body. For example, ices can hold together silicates or metallic grains. In such a case the body will start to break apart during the flight and then each part creates its own shock front and melts away. This fragmentation often happens at surprisingly high altitudes, already above 100 km altitude (Qian, Ross, Boyi, & John, 2016; Stokan & Campbell-Brown, 2014). The third possibility is that the pressure gradient between the front and the back of the body becomes larger than the internal body strength of the solid material, which results in a sudden catastrophic disintegration of the entire body. This releases a large quantity of small debris and gases that immediately start to evaporate and undergo chemical reactions. From distance, this is seen as an explosion or a bright flare. If the body was big enough and strong enough to avoid complete disintegration during that process then some fragments would keep flying until they slow down to subsonic speeds and fall as meteorites. On the other hand, the tiny melted parts of the disintegrated body can slowly being deposited to the ground in a form of microscopic particles called microspherules. These scenarios can be deduced from observations by solving for α and β meteor coefficients, as described in the previous section.

Notice how all these descriptions of meteor are assuming some bulk physical and chemical properties either of the meteoroid body or of the meteor gas. Attempts to go deeper in understanding the meteor microphysics are relatively scarce. There are two main reasons for that. The first is that the underlying physics is very complex and it requires lots of effort to achieve meaningful breakthroughs. The second problem is how to obtain high-resolution (spatial, temporal, spectral) observations that would guide the theory. Fortunately, the never-ending technological advancements lead to new sensors capable of collecting huge amounts of data with better resolution.

A vivid example of what kind of a surprise a new type of high resolution sensor can bring to the meteor physics is the discovery of a large halo around a Leoind meteor by Stenbaek-Nielsen and Jenniskens (2004). They observed Leonids in 2001 with a 1000-fps high-speed camera and image intensifier. The setup was developed for auroral research and used for meteors in this case. They managed to record a meteor that showed a halo up to 1 km away from the meteoroid at the altitude of about 105 km. The atmospheric density at these altitudes should not allow a glowing meteor plasma ball (i.e., meteor head) larger than several meters. Thus, this halo was not expected and it is not clear what can create light emission at such distances from the meteor head.

The authors mention two possibilities: the meteor could produce UV light that excites the surrounding atmosphere to glow or somehow the Earth's magnetic field might be involved in the process of spreading the plasma effects further away from the meteor. In both cases they also find limitations to these ideas and conclude that there is no plausible explanation. The role of magnetic fields is indeed poorly explored even though we know it should not be ignored. Meteors ablate mostly between 75 and 125 km altitude where ionospheric electrons are decoupled from the neutral gas. Instead, they are trapped into gyration by the Earth's magnetic field as their collision frequency is smaller than the electron cyclotron frequency. On the other hand, ions at these altitudes are coupled to the neutral gas since they have large enough collision frequency to dominate over the ion cyclotron frequency. Above about 130 km both the electrons and ions are trapped into gyration and this certainly should affect the phenomenon of high-altitude meteors. But at 105 km altitude, where the curious case of meteor halo was seen, electrons and ions behave differently. This has been explored recently theoretically for micrometeoroids (Sugar, Oppenheim, Dimant, & Close, 2019) and meteor trails (Oppenheim & Dimant, 2015), but not for ordinary meteors, where the hypersonic slip-flow regime is operating.

However, a recent work by Šiljić, Lunić, Teklić, and Vinković (2018) opened a theoretical possibility for new meteor physics behind the Leonid halo phenomenon. They derive an argument for a charge separation in the meteor head due to the before mentioned differences between the electron and ion magnetization. This leaves the meteor head plasma with a net charge, which in turn accelerates protons (that exist in the meteor plasma). The accelerated protons are ejected out of the meteor head and go through a series of collisions with the atmospheric species until they thermalize into the background. These collisions result in excitations and light emission, similar to the proton aurora. They also showed how the UV light indeed cannot explain the halo.

The idea that meteor plasma can acquire a net charge is not new, albeit on the fringe of meteor science, but this is the most detailed description of a possible mechanism for this process to occur. The authors argue that, if charging indeed exists, it would manifest itself in some other meteor-related phenomena. For example, they show that the amount of charging would be inclined to oscillate, which might explain pulsations of the meteor head plasma detected using tristatic 930 MHz EISCAT UHF radar system (Kero et al., 2008) or millisecond flares seen in the high-resolution meteor photometry (Spurný & Ceplecha, 2008). In case of fragmentation, the fragments might repel each other and acquire high transverse speeds as detected in some cases above 100 km altitude where such speeds should not be possible otherwise (Stokan & Campbell-Brown, 2014). Also, a strong net charging of a meteor perturbs the surrounding ionosphere that can result in a propagation of the electric field perturbation toward lower altitudes, which could explain a possibility of meteors triggering sprites (Suszcynsky et al., 1999).

Conclusion

Despite the meteor astronomy being one of the oldest astronomy subdisciplines, our understanding of meteors and meteor-related phenomena is far from satisfactory. The inability to peek into the fine details of meteor plasma properties prevents us from deducing intricate details of physical and chemical processes of meteor–atmosphere interaction. Improvements require investments into a more diverse set of instruments, interdisciplinary approach and large multi-instrument campaigns. This means more advanced experimental setups and collaborations are needed, using more advanced camera systems on the ground to obtain high-quality high-resolution images, spectra, trajectory triangulations and photometry. Instruments need to be put into space, too, as this allows the overview of a larger area and the detection of spectral regions that cannot be seen from the ground (e.g., UV spectrum). These shorter wavelengths need to be augmented by radio wavelengths, were radio telescopes and radars penetrate the meteor plasma and provide information on its properties. Meteor–ionosphere interaction needs more attention, with ELF/VL/LF monitoring to reveal correlation with individual meteors.

The benefit of opening new instruments in meteor study has been demonstrated recently by an unexpected discovery of a radio afterglow of meteors in the HF band (3–30 MHz) and VHF band (30–300 MHz) by the LWA1 radio telescope (Obenberger et al., 2014). Meteors have not been a part of the science case for this telescope, but the correlation between some transient radio burst and images from meteor cameras revealed the existence of a previously unknown phenomenon. Meteor astronomy is so rich in valuable information about the Solar System and the Earth's atmosphere that it should be an integral part of the science cases for large astronomical facilities. For example, meteors are integrated into the science case for EISCAT_3D (McCrea et al., 2015), a large radar system in Scandinavia (with separate stations in Norway, Sweden, and Finland) for the scientific study of the Earth's atmosphere and ionosphere. Similarly, Bektešević, Vinković, Rasmussen, and Ivezić (2018) showed how the LSST telescope (Legacy Survey of Space and Time, n.d.) will resolve meteors and be a great instrument for studying meteors. However, the incorporation of meteor science into large astronomical facilities requires a significant investment into Big Data tools to extract the meteor data—from algorithms to dedicated personnel (Vinković et al., 2016).

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