BRAIN-BE : METRO - **Trajectories of meteors and their origin**

SUMMARY

Context :

The cumulative mass deposited by meteoroids in the Earth's atmosphere every day is of the order of 100 tons. These particles influence the chemistry in the upper atmosphere. They allow sampling the temperatures and winds in that region, which is inaccessible via balloons or spacecraft. Outside the atmosphere, they pose a threat to spacecraft and astronauts in orbit. They also allow studying the evolution of interplanetary dust and specific comets or asteroids crossing Earth's orbit. The physics of meteor ablation during hypersonic entry into the atmosphere is of great interest for the re-entry of spacecraft or man-made debris. The METRO project proposed to study meteoroids using radio data collected by BRAMS, a network of Belgian radio receiving stations using forward scatter techniques to detect and characterize the meteoroids. The network comprises one dedicated transmitter and a large number of receiving stations spread all over the Belgian territory. The project also proposed to advance models of the meteor phenomenon and to confront them with the data.

Objectives :

The main objectives of the project were to:

- Determine the trajectories of meteors from data continuously acquired by the BRAMS network.
- Compare radio observations with optical observations provided by networks such as CAMS-Benelux or FRIPON which cover the sky above Belgium.
- Obtain the ionization profile along an individual meteoroid path from multi-station observations of the same meteor, to compare the results with those obtained from an ablation model and to use optimization methods to get an estimate of the initial mass of the meteoroid before it enters the atmosphere.
- Develop comprehensive physico-chemical models and methodologies for the description of the meteor phenomenon in the rarefied and continuum regimes, with application to radio detection. By doing so, we want to reduce the initial uncertainties relevant to i) the input of metals in the chemistry of the upper atmosphere, ii) the resulting ionization efficiencies and plasma dissipation rates, which are necessary for a correct interpretation of radar and radio detection measurements.
- Compute fluxes of meteoroids, which is extremely relevant for spacecraft in orbit.

Methodology :

In order to retrieve trajectories of meteoroids using solely BRAMS data, the first step is to develop algorithms to automatically detect the enormous number of meteor echoes in the BRAMS data. Several methods using purely geometrical factors, timing and data from a radio interferometer have been considered. A comparison of BRAMS radio data with optical observations from the CAMS-Benelux network also allows a detailed analysis of the power profiles of the meteor echoes and a preliminary comparison with the results obtained with, e.g., the simulations done at VKI. The study of the power profiles of underdense meteor echoes (the majority of echoes detected by the BRAMS network) gives access to various parameters such as the ionization at the specular reflection point.

From multi-station observations of the same meteor, an ionization profile can be obtained and compared to results from an ablation model, giving an estimate of the initial mass of the object.

To support observations, meteor simulations are performed using the computational tools developed at VKI: a Direct Simulation Monte Carlo (DSMC) code for meteors at high altitudes where the gas is rarefied, and a stagnation line fluid code coupled with radiative heat transfer at low altitudes. Parametric studies are performed and results compared with data available in the literature. The development of gas-surface interaction models is assisted by ablation experiments in the VKI Plasmatron facility and multi-scale analysis of the deteriorated material.

The first step towards meteor fluxes is to compute the Observability Function (OF), which takes into account the geometry of the observations to transform raw meteor counts into real ones. The sensitivity of the whole system should also be included to compute meteor fluxes.

Main results :

A massive set of data has become available and archived at BIRA-IASB, with nearly 10 years of data. The network has also continuously been extended and upgraded to produce high-quality data. The next generation of stations using a new type of receivers is ready.

Two algorithms for automatic detection of meteor echoes have been developed. A first implementation is planned soon to produce daily activity curves for each BRAMS station. During meteor showers, the Radio Meteor Zoo, a citizen science project launched in 2016, has allowed us to study the activity of the principal meteor showers during several years in a row.

The problem of multipoint trajectory determination has proved to be more difficult and is tightly coupled to the spatial organization of the network. Three methods have been developed. Soon the use of a meteor radar, currently in development in Dourbes, will provide a fourth method to reconstruct trajectories. The verification of BRAMS trajectories with those obtained using data from CAMS-Benelux or FRIPON will be easy as we are actively cooperating with these networks.

A study combining optical CAMS-Benelux and radio BRAMS data has been carried out. Techniques have been developed to obtain the power profiles of meteor echoes from BRAMS raw data. From the peak power measurements, the ionization at the specular reflection points can be obtained.

We have provided a detailed computational description of the meteoroid degradation process and those physico-chemical phenomena that drive the dynamics of the ablated vapor around the body and in its plasma trail. Ionization efficiencies, luminosity, and trail dissipation rates obtained with this computational approach have been compared with observational data in the literature. Thermodynamic, transport, and kinetic data have been computed for the species relevant to meteoroid ablation, and they are available in the framework of the Mutation++ library. We have devoted particular attention to the investigation of gas-surface interactions. This investigation has been supported by ground experiments in the VKI Plasmatron wind tunnel and NASA Ames facilities. Comparison with the experiments has enabled validation of the developed models and substantial insight into the involved phenomena.

The geometric part of the OF is nearly ready. All the technical parameters, such as antenna gains, the sensitivity of the receiving chain, etc., are available for computing meteor fluxes from radio observations.

Conclusions :

The METRO project has significantly helped to advance the BRAMS system into an internationally recognized research facility. The project has provided a stimulus in four areas:

- Improvements in the BRAMS hardware: better calibration, recommendations for the best localization of new observing sites
- Improvements in the data treatment through automated data processing tools
- Improvements in the scientific interpretation of the data
- Strengthening active collaborations with the optical networks in Belgium such as CAMS-Benelux and FRIPON.

At the same time, the simulations and the laboratory experiments that have been conducted have led to a further strengthening of Belgian expertise in the area of hypersonic re-entry, a topic of strong interest for spaceflight.

The METRO project has offered many side results:

- Strengthening pro-am collaboration, involving public observatories and amateur astronomers in the BRAMS network, which are all involved in promoting STEM education.
- Boosting the development of the Radio Meteor Zoo, a citizen science project, offering the interested citizen and taxpayer to be directly involved in the research activities.
- Offering the opportunities for 6 students to perform a BRAMS related project, supporting 1 Master Thesis, and 2 PhD theses to be involved in this research topic.

This project has put together the fundamental tiles of a broader and ambitious modeling effort that will help astronomers to reduce uncertainties in the interpretation of radio echoes, paving the way towards the adoption of more sophisticated computer simulations in the field of meteor science.

Recommendations :

- Extend and improve the BRAMS network continuously.
- Maintain and strengthen the Pro-Am collaboration.
- Finalize efficient and reliable reconstruction techniques for meteoroid trajectories
- Apply the OF to meteor showers. Calculate meteor fluxes in a long-term project
- Use information from the power profile of meteor echoes to provide mesospheric temperature measurements and maps of mesospheric winds above Belgium. Include these results in a more global (European) context.
- Continue comparisons of fireball data obtained with FRIPON and BRAMS.