Big data era in meteor science

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Over the last couple of decades technological advancements in observational techniques in meteor science have yielded drastic improvements in the quality, quantity and diversity of meteor data, while even more ambitious instruments are about to become operational. This empowers meteor science to boost its experimental and theoretical horizons and seek more advanced science goals. We review some of the developments that push meteor science into the big data era that requires more complex methodological approaches through interdisciplinary collaborations with other branches of physics and computer science. We argue that meteor science should become an integral part of large surveys in astronomy, aeronomy and space physics, and tackle the complexity of micro-physics of meteor plasma and its interaction with the atmosphere.

1 Introduction

Exploration of meteor physics and meteor related phenomena has reached the level of complexity that requires new experimental and theoretical advancements. There is a clear demand on more reliable data on meteor plasma and meteor-atmosphere interaction, as our current understanding of these physics is not comprehensive. The recent increased interest in meteor science triggered by the Chelyabinsk airburst (Borovička et al., 2013; Brown et al., 2013; Popova et al., 2013; Proud, 2013; Antolik et al., 2014; Kohout et al., 2014) helps in building the case for technologically and logistically more ambitious meteor projects. This requires developing new methodological approaches in meteor research, with Big Data science and close collaboration between geoscience and astronomy as critical elements. We discuss possibilities for improvements and promote an opportunity for collaboration in meteor science within the BigSkyEarth[1] network.

2 Big Data I

High-resolution and high-sensitivity meteor detections with high-precision photometry exist on images from big telescopes that resolve the meteors. For example, Iye et al. (2007) used the 8.2 meter Subaru telescope's 80 mega-pixel SuprimeCam camera and observed 13 faint meteors in 5 days. This proves that meteors are quite common stochastic feature in such images, but they are treated as a noise and stay untouched and unexplored. Finding them requires an automatic search for meteors in large astronomical databases. A recent example is an ongoing search for meteors in the SDSS database[2] (Bektešević, 2015), which required a development of a new machine recognition procedure for linear feature detection (Bektešević et al., 2016). Many other databases can be targeted by that approach, but this requires techniques in the domain of Big Data methodologies, where a small number of events has to be detected within terabytes or petabytes of imaging data. The upcoming big surveys covering the time domain in addition to large sky coverage will also have a daily stream of transient events alerts (e.g., LSST). Many current surveys too have such streams, either public (e.g. CRTS) or private (e.g. iPTF and Pan-STARRS). In fact searches on PTF data have been carried out to look for comets (using extendedness, Waszczack et al., 2013), and similar searches are on for asteroids (using streakiness), and a program has begun to get the missed ones using machine-learning. The meteor science community could be actively involved in these big sky survey collaborations and make an effort to put meteor detection into the surveys' automatic image recognition pipeline.

[1] http://bigskyearth.eu/

[2] http://vinkovic.org/Projects/MindExercises/radnje/2015_Dino.pdf

3 Big Data II

A recent discovery of MHz emission from meteors in the VHF radio band (Obenberger, 2014) demonstrates the need for monitoring possible meteor signals in sky surveys outside the traditional visual bands and comfort zone of meteor astronomers. The nature of this emission is not understood, but it shows the richness of meteor plasma physics. The ongoing and upcoming radio sky surveys will produce petabytes and soon exabytes of data (LOFAR, SKA). The meteor science community could pursue projects that combine meteor detection with different types of sensors simultaneously to extract more complex science from the data and to obtain precise timing of meteor appearance required for extracting data from big sky survey databases.

4 Big Data III

A search for dark energy and large-scale structure of the Universe as well as investigation of Galactic structure has motivated the development of specialized massively multi-object spectrographs equipped with several thousands of rapidly fixable fibres or Integral Field Unit spectrographs (IFUs). While some of them have very small field of view (e.g. 1 arcmin for ESO MUSE), other have several degrees, e.g. LAMOST[3] survey contains 4000 fibres of over 5°, the planned HETDEX survey even 33600 spectra in 22 arcmin (Adams et al., 2011) . Those systems are running wide-field spectroscopic surveys with an exposure time of tens of minutes to several hours. As the observation is continuously running for months or years, there is a high probability that many meteoric spectra were registered by them, which are, however hidden in the noise. Serendipitous observations of meteors with such instruments are of a great value, since the individual spectra can reveal differences in emission from various parts of the resolved defocused meteor image.

The spectra are reduced by automatic pipelines, with automatic matching of significant features like strong emission (for redshift estimation) and/or global matching with a library of templates (for stellar classification), but always individually, one spectrum independently of others. As the targets are usually faint, the signal-to-noise ratios are low and so the meteoric spectrum will be hidden in the noise. However, the potential of the astroinformatics approach is in finding the correlations in intensity of noise among all fibre spectra exposed during the same exposure, which are in addition correlated with position of fibres on the sky. So the data have a character of a sparse data cube – looking like an image, where every point contains a whole spectrum (the spatial coverage is regular grid in case of IFUs).

Finding such correlations is a challenge for advanced statistics and big data processing. The probability of such a detection requires analyzing of an enormous amount of data (of the order of hundreds of TB), which must have a

[3] http://www.lamost.org/public/?locale=en

unified metadata description. The great advantage of such a novel approach is in the possibility of observing changes of spectra of the meteor along the orbit while passing over different fibres or IFU elements.

This type of meteor astronomy requires new algorithms for meteor detection and analysis of their multispectral data as well as involvement of experts on advanced statistics and informatics understanding scientific Big Data processing.

Enormous potential, yet unexploited, presents the cross-matching of all such surveys in a global manner, with an aim to find observations of the same regions of the sky at the same time with different instruments, namely at the moment of a bright meteor detection in the wide field surveys. This may be feasible, if all the surveys follow the standards of the International Virtual Observatory Alliance (IVOA), namely the Table Access Protocol (Nandrekar-Heinis et al., 2014) operating on Observation Data Model Core Components (Louys et al., 2011) designed for temporal, spectral and spatial description of virtually all types of astronomical data.

We also suggest considering dedicated observation projects with middle class telescopes, with the telescope focus set onto the meteors. From SDSS statistics we see that the distribution diverges from the prediction from major meteor storms. I.e., there are a number of telescopic meteor storms with a small size distribution, which can dominate the optical groups in the telescopic magnitude range. The optimal strategy might be to make predictions from sky surveys and other detections, and to allocate the telescope time to the peaks of telescopic meteors. Even with a Schmidt telescope with 180 cm focal length, the sharp picture of a meteor at 110 km distance is 3 millimeters behind the sharp images of stars, leading to a blurred image by approximately 3 arcsec. The blurring keeps worsening heavily with the increasing focal length. A well-focused telescope can, on the other hand, reach a few 10 cm resolution, which is a solid observational basis for studying the plasma trail.

5 New meteor plasma physics

There is mounting evidence that our understanding of the meteor plasma physics is not adequate to explain various meteor related phenomena. High altitude meteors at about 130 km altitude have been explained by sputtering (Popova et al., 2007; Vinković, 2007), but some images show jets and structures that require additional explanations (Spurný, 2000). Similar fast jets have been detected at lower altitudes too (LeBlanc et al., 2000), and a complex plasma dynamics in the rarefied magnetized ionospheric environment might be the reason. Maybe this physics has some connection to the phenomenon of electrophonic sounds, which had been detected instrumentally, but their explanation is still missing (Zgrablić et al., 2002). The main problem is that this sound seems to originate from strong electric fields on the ground, but created at ionospheric altitudes. However, such strong quasi-electrostatic disturbances should not be able to propagate to the ground. Also, fragmentation above 100 km altitude can explain some radar or imaging data, but there is no explanation for detected high speed fragments at these altitudes (Stokan and Campbell-Brown, 2014). Similarly, fast (millisecond) high-amplitude flickering of light curves (Spurný and Ceplecha, 2008) and stationary oscillations of radar cross section (Kero et al., 2008) are still not explained. A large halo around a meteor detected in a high-speed recording (Stenbaek-Nielsen and Jenniskens, 2004) is probably connected to the same type of physics. A new theoretical model (Šiljić et al., 2016) seeks explanation for many of these phenomena in electromagnetic coupling between meteors and their surrounding ionosphere, where the Earth's magnetic field plays an important role.

The most up-to-date papers detailing radiation physics of meteors are still the works by Öpik (1933, 1955), though of course there exist many studies, where not yet well-known processes are simply modelled using a heavily increased number of free parameters. The use of scaling laws to formulate a well-posed inverse problem helps in finding some key meteor parameters (Gritsevich, 2009; Gritsevich and Koschny, 2011), but there is still room for improvement. The meteor trails are also a complex topic.

The magnetization of trail electrons results in their faster drift along the direction of the magnetic field, which has been detected by radars and simulated recently in 3D (Oppenheim and Dimant, 2015). Theory also shows that strong electric fields could be induced with the trail, which can drastically increase the complexity of meteor plasma dynamics (Dimant et al., 2009). Such a long list of unexplained meteor related phenomena suggests that our understanding of meteor plasma and hypervelocity shock physics in rarefied partially ionized and partially magnetized ionospheric plasma is not complete. The variety of detection techniques required for measuring these phenomena argues for a highly interdisciplinary approach with a combination of astronomical and geophysical techniques.

6 Numerical simulations

The recent development of numerical simulation methods and enhanced computational resources provide possibilities to forecast the meteor plasma dynamics and to test how changes in the atmospheric conditions affect the meteor radar reflections and explain unexpected results in the observations. Computer simulations, built by using modern and computationally efficient methods (see, e.g., Marshall and Close, 2015; Sansom et al., 2015; Räbinä et al., 2016), are reasonable tools to test new meteor plasma models and consider, e.g., the fragmentation of a meteoroid into smaller pieces (e.g. Kero et al., 2008; Zhu et al., 2016). However, when it comes to simulations of hypersonic meteor flight, numerical simulations are often scarce and simplified. These simulations can reveal details of the meteor non-equilibrium plasma formation and its properties and composition, but it is a highly complex problem. The meteor plasma physics includes a plethora of phenomena

– collisional processes between various charged and neutral plasma species; processes of atomic and molecular excitation, dissociation, ionization and recombination; evaporation (ablation) of the meteoroid surface; thermal radiative processes and transfer; chemical and charge exchange reactions; dusty plasma effects; etc. – and all that coupled with internal and external electric and magnetic field dynamics that influence election and ion mobility in different ways, depending on the ratio between their collision and cyclotron frequency. Not surprisingly, the meteor hypersonic flight simulations have been simplified to include only basic kinetics of atmospheric and meteor vapor species (Boyd, 2000; Vinković, 2007; Dyrud et al., 2008) or, in its most advanced version, a radiative gas dynamic model of physically and chemically non-equilibrium flow at lower meteor heights (70 km) where the atmosphere is dense enough to fulfil conditions for ignoring external electric and magnetic fields and for applying simulation methods developed for modelling the re-entry of space vehicles (Surzhikov, 2014). Hence, we still do not have numerical simulations that can address the issues of meteor plasma at typical heights between 70 and 130km, where: the flow is in a transition regime from free-molecule to continuous flow (Popova et al., 2000); electrons react to the external magnetic field while the ion mobility is still collisional dominated; we expect a self-induced electric field within the meteor's diffuse shock front (Farbar and Boyd, 2010). These new simulation frontiers are required to test the latest theoretical attempts of exploring the impact of the ionospheric electric and magnetic field on the meteor plasma dynamics (Dimant et al., 2009; Šiljić et al., 2016).

7 Complex connection with other atmospheric phenomena

Although the majority of meteors are sub-millimeter in size, they still have a great importance for the Earth's atmosphere. They are the main source of metallic ions for the ionospheric Sporadic E layers -– thin layers of metallic ion plasma which form mostly between 100 and 125 km (Haldoupis, 2012). Meteor airbursts create a plethora of large scale atmospheric and ionospheric disturbances. Meteor storms can significantly disturb the ionosphere and its ionization levels (e.g. Baumann et al., 2013; Pellinen-Wannberg et al., 2014). Nanometer size smoke particles from meteor ablation influence ion chemistry at altitudes from 80 to 120 km and are most likely nucleation sites for ice particles that make up noctilucent clouds (Hervig et al., 2012). It is also confirmed now that meteors can trigger sprites (large-scale electrical discharges high above thunderstorms), although the exact physical mechanism enabling this phenomenon is not understood (Qin et al., 2014). These examples demonstrate the complexity of the meteor-atmosphere interaction that goes far beyond meteor ablation physics.

8 Three dimensional radar observations

Radars play a critical role in the exploration of meteor plasma properties – from meteor head to meteor trails. A new dimension of meteor plasma exploration has been reached with a simultaneous usage of three radars. The potential observing capabilities of a radar system are evaluated by McCrea et al. (2015), McKay-Bukowski et al. (2015) and Pellinen-Wannberg et al. (2016). The authors address an important topic of improving the estimates for the flux of extraterrestrial matter to the Earth based on the data obtained using a high-power radar system. EISCAT_3D (Europe's Next-Generation Radar for Atmospheric and Geospace Science) is incoherent scatter radar and it is expected to be one of the most advanced instruments to investigate plasma physics phenomena in the terrestrial atmosphere. The multi-beaming capability makes it possible to perform three or more tri-static observations at different heights simultaneously, while the lower operating frequency makes head echoes observable at heights up to 115 km.

9 Meteorite fall location using weather radar imagery

This is a recently proven approach to locate fresh meteorite fall (Fries and Fries, 2010; Fries et al., 2014). Weather radars are operated by national weather bureaus worldwide and have assisted in the recovery of several meteorites in the United States within the past years, including the Sutter's Mill and Battle Mountain meteorites. Up to now the search for the specific signatures within the data acquired by weather radar has been performed manually and was initiated due to the existence of the other fireball records indicating a possible meteorite fall (i.e. by having the time and tentative location constrains available from the other observation means). However dedicated automatic software may be developed to recognize the 'meteorite signature' in the whole set of weather radar data and to calculate timely the locations and create immediate alerts for detected meteorite falls.

10 Emission and/or scattering of VLF

Very low frequency (VLF) radio waves have been occasionally explored in relation to meteors. The interest for this topic initially emerged from theoretical predictions of VLF being the cause of electrophonic sounds. However, their relation to meteors has not been firmly established and they have not been detected concurrently with electrophonic sounds. Instead, even lower radio frequencies (in the range of quasi-electrostatic fields) are suspected as the source of these sounds (Zgrablić et al., 2002). Two types of possible correlations between VLF and meteors have been implied: meteors emitting VLF waves (*case a*) or their perturbed surrounding simply scatter the atmospheric VLF waves (*case b*) producing the variations of amplitudes and a phase of kHz VLF signals. With a VLF receiver or network of receivers (Šulić et al., 2016) we can continuously monitor and later analyze these meteors correlated VLF radio waves.

Case a

First we consider the electromagnetic detection of meteors. Recently, it was reported that a meteor shower produces ELF/VLF waves which propagate and reach the ground. It has been shown that 35% of observed meteors and corresponding VLF events are in correlations. However, more data with a statistical approach and further investigations are needed to confirm the statement that the process of possible detecting meteors with the help of an electromagnetic spectrum has potential to become a widely useful tool. In spite that it is at a very noisy frequency band (lot of EM waves produced in this band by other sources like lightning, electrical circuits, power supplies) this possible technique would have the advantage over the visual detection because it can be applicable at any time day/night and in almost all weather conditions. A dynamic VLF spectrum with broadband data is shown in *Figure 1*. With the help of this spectrum we can get all frequencies between 5 kHz and 13 kHz (possible emitted by meteors) compare and process them. This kind of data, i.e. a large volume of spectral images with spectral wavelengths, takes up a few GB per hour and requires complex processing and analysis.

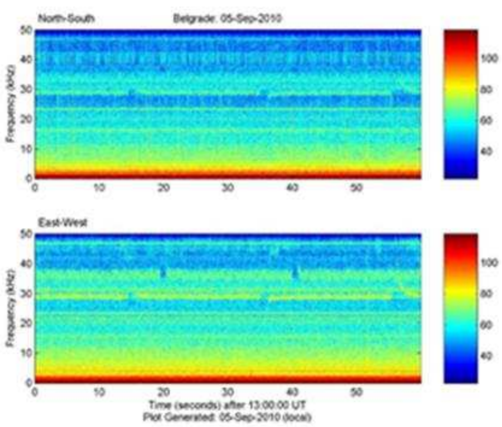

Figure 1 – Broadband data includes information at all frequencies between the systems cutoffs (few Hz – 47 kHz) recorded at receiver site.

Case b

Possible detection of meteors can be done by simply taking the amplitude and phase, separately (of a single narrow frequency range, specified in the software, and usually corresponding to the frequency of a VLF transmitter which can be seen from the map in *Figure 2*) and compared to the non-perturbed level. This can be quite improved with a simultaneous usage of different transmitters i.e. the usage of signals from different directions (path dependent) in order to really collect correlation between signal perturbation and meteor detection.

The physical explanation-mechanism for case b demonstrates the complexity of the meteor-atmosphere interaction (meteor plasma, ionization, triggering sprites, etc.). Meteor particles, due to collisions and perturbation of the surrounding ionosphere (neutral molecules), pass the kinetic energy and convert into potential energy of ionization with the production of extra ionization in the ionosphere. Meteors and this extra ionization produced by them during their passage through the lower ionosphere may have been the cause of high variation of signal level of amplitudes /phase of VLF signals in the Earth–ionosphere waveguide (recorded after their journey through a long distance), which is few times its normal value (De et al., 2012).

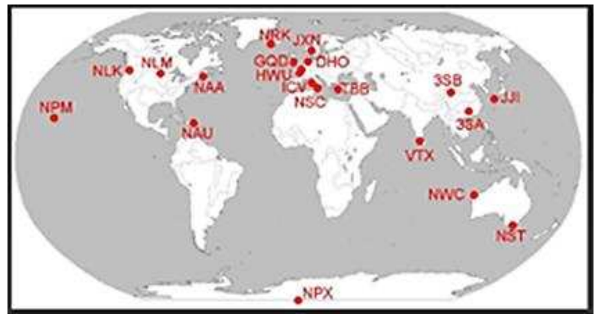

Figure 2 – Worldwide VLF transmitters.

It would be very useful for VLF researchers to make effort and implement some new solutions which are already used in other fields of astro- and geoscience, such as events alerts (e.g., CRTS). It was with the Palomar-QUEST, and CRTS that the VOEvent protocol was developed and implemented under the aegis of the US Virtual Observatory (NVO, VAO). The VOEvent (Williams and Seaman, 2006) is a simple and small packet describing the what/where/when/how/why of an event and can be conveyed as a variety of inter-transferable structured data-formats such that humans as well as machines that can make decisions and automated telescopes can receive them. CRTS, for instance, has made extensive use of it (Drake et al., 2009; Djorgovski et al., 2011; Mahabal et al., 2011). Recent systems like Gaia are using variations on the theme, and LSST plans to use an extended version to also include small image cutouts. We propose to the meteor science community more networked VLF observatories for a better understanding of this phenomenon and we propose a highly interdisciplinary approach utilizing the infrastructural developments in optical astronomy as mentioned above. The VLF event alerts can be combined with alerts of meteor detection coming from meteor networks. Such networks of video cameras are now established in many countries and often operated by amateur astronomers. The networks detect meteors and their trajectories and provide invaluable data for meteor activity and their origin exploration. But they can be further utilized as targets of meteor VLF events. A network observing the sky on the path of VLF signals from transmitters can feed the VLF observer with meteor detection alerts. In case ionization from a meteor shower or from bright individual meteors creates disturbances in the VLF signal, the cross-correlation between meteor and VLF alerts would reveal details of the physics behind this connection. However, such a coordinated work is not challenging only from logistical point of view, but also from a Big Data perspective.

There is also an active radio observation of meteors ongoing in the VHF range using the French military satellite tracking radar system GRAVES at 143.05 MHz. An example of such VHF activity is the Czech radio meteor detection network Bolidozor (Pinter et al., 2013; Kákona et al., 2015). The primary goal of this network is calculation of meteor trajectories from multi-station meteor radio echoes. Bolidozor stations' and receivers' configuration is shown on *Figure 3a and 3b*.

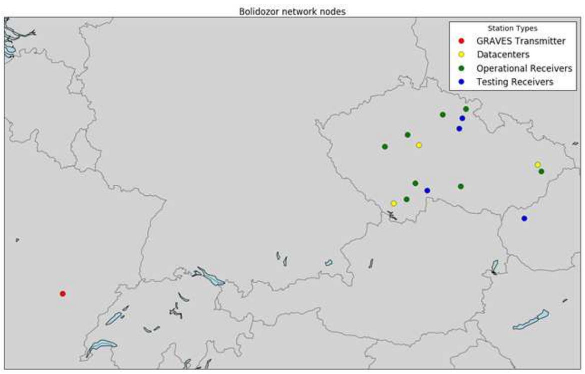

Figure 3a – Czech VHF meteor detection network Bolidozor. The red dot in France is the VHF transmitter GRAVES.

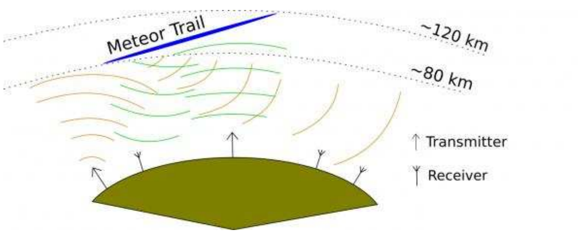

Figure 3b – The core of the system is made of a network of meteor radio detectors that are gradually upgraded and extended to contain new measurement methods.

The network is technically limited mainly by signal processing algorithm implementation because the multi-static systems require numerically demanding statistical calculations, which are furthermore being done in real-time and with a signal containing a high proportion of interference. Each station currently generates 1GB of pre-filtered data per day. The data are accumulated in a central data server located at the Ondřejov observatory. In order to effectively use the multi-static signal, there have to exist algorithms able to detect objects covered by interference and using the data from multiple stations, but the data processing complexity requires a high amount of computing power which is usually in the form of distributed computing power in modern scientific experiments, e.g. BOINC[4]. Such computing methods require data distribution on multiple nodes, which means the distributed storage of a big data amount, is necessary for such system. One of the promising, less computationally demanding methods seems to be an application of artificial neural networks (Roman and Buiu, 2014). However the research is just at the beginning and therefore there are many tasks open from the informatics point of view.

11 Solar migration

The study of meteors can also help inform the study of the Galaxy we live in. There is a growing consensus that the Milky Way has experienced significant levels of stellar radial migration, with stars having changed their orbital radius within the Milky Way significantly while retaining nearly circular orbits (Roskar et al., 2008; Hayden et al., 2015; Loebman et al., 2016). However the exact extent to which stars have migrated, particularly in the Solar neighborhood, is not well known. In much the same way as stars migrate, interstellar meteoroids will also have. A small, but not negligible, fraction of meteors reaching the Earth will originate from across the Milky Way, giving us direct access to conditions across the Milky Way. Properties, such as the relative abundance of alpha-elements (for instance, carbon, oxygen, magnesium, and calcium) compared with iron-peak elements, vary across the Milky Way, providing a means by which the origin within the Milky Way of meteors can be recognized. Such meteors at the Earth are therefore particularly useful for helping to constrain the extent to which migration has been taking place in the solar neighborhood.

12 Detection of meteors from orbit and stratosphere

Certain aspects of meteor science require observations outside the atmosphere, or at least above the majority of the atmosphere (Bouquet et al., 2014; Vaubaillon et al., 2015). For example, observations from satellites enable detection of meteor UV spectra and infrared signatures (Rambaux et al., 2014). In comparison with existing ground-based observations, a space-based optical system for meteor detection would escape dependency on weather and atmospheric conditions, critical not only for detectability, but also for subsequent data analysis (Lyytinen and Gritsevich, 2016). It is also the easiest way to set up meteor observations on other planets (Christou et al., 2012, 2014). Bouquet et al. (2014) recently evaluated potential performance by such systems as a function of observation parameters (optical system capabilities, orbital parameters) and considering a reasonable range of meteoroid properties (mass, velocity, composition) determining their luminosity. The authors developed a numerical tool called SWARMS (Simulator for Wide Area Recording of Meteors from Space) and calculated optimistic meteor detection rates for two different systems: the SPOSH (Smart Panoramic Optical Sensor Head) camera optimized for the observation of transient luminous events (Oberst et al., 2011; Christou et al., 2012), and the JEM-EUSO (Japanese Experiment Module – Extreme Universe Space Observatory) experiment on the International Space Station (ISS).

We also propose the creation of a stratospheric platform for meteor observations put on an autonomous unmanned airship. This would enable observations in a rarefied

[4] http://boinc.berkley.edu

atmosphere, above the majority of water vapor. Under such conditions meteors can be observed close to the horizon and with infrared detectors. Airborne meteor observations have a long history (Clifton, 1971; Millman, 1976), but it was the NASA MAC campaigns targeting Leonid showers that transformed airborne meteor science into a mainstream science (Jenniskens and Butow, 1999). This campaign has expanded in its scope and it is now using various types of aircraft[5] for observing meteor showers and it recently helped organize the first European airborne meteor observation campaign (Vaubaillon et al., 2015). The airborne platforms have an advantage of avoiding clouds and have access to a reduced air-mass of water vapor. This enables sampling of a large volume of atmosphere in search for meteors closer to the horizon. It also enables observations of meteor light-curves and spectra in wavelength regions typically inaccessible due to atmospheric water vapor.

A stratospheric airship would provide an entirely new direction in airborne meteor observations. Unlike airplane campaigns that last for a few days, such an airship would provide a continuous service over the year. It would also reach higher altitudes, nominally about 20 km above the sea level. And it would be much cheaper to operate it and maintain. Its science case would not be just meteor observations, but also a multitude of other topics in astronomy (e.g. infrared astronomy, where the need is already demonstrated by the SOFIA airborne telescope (Gehrz et al., 2009)), aeronomy (e.g. transient light phenomena above thunderclouds), Earth observation and remote sensing (e.g. continuous high resolution ground monitoring of about 4000 km^2 not possible with the current drone, airplane or satellite observations) and meteorology (e.g. continuous measurements of atmospheric conditions at high altitudes and during landing/rising maneuver). Such a stratospheric platform would be also ideal for testing various new technologies/instruments aimed for future deployment on satellites.

The key technical characteristics of the proposed airship are already provided by Hipersfera Ltd.[6], a company uniquely specialized for this type of autonomous unmanned aerial vehicles. The airship would host a stable payload platform for about 12 hours (during night time in case of astronomical observations), followed by a landing maneuver and just a few hours for maintenance, repair and overhaul procedures. This makes the airship ready for a new mission every day. The payload capacity would be 100 kg, with 5 kW of continuous and 7-10 kW peak electric power supply. The airship design allows mounting of useful payload either on the bottom or on the top side of the airship. Instruments of a small weight (simple sensors) can be attached on a side. The airship has a rigid structure with attached vectored thrust for attitude and position control. The stabilized payload platform (e.g. designed as a Stewart platform) is connected to the airship through passive vibration isolation, which improves on the default 0.2–0.5 deg/s stability achieved with the vector thrust. The vibration isolation can be further improved on request (e.g. with 3- or 5-axial gimbal). The airship design is scalable, which means that a larger payload can be achieved simply by scaling up the airship volume.

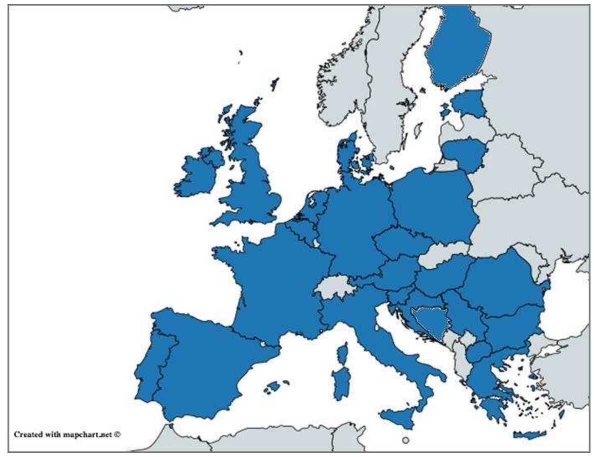

Figure 4 – The map showing COST member countries participating in the COST Action BigSkyEarth (as of June 2016). Further information on BigSkyEarth and its activities are given at http://bigskyearth.eu/.

The TD COST Action TD1403 "Big Data Era in Sky and Earth Observation" (BigSkyEarth, *Figure 4*) network offers an excellent platform to develop the stated big ideas for possible future advances in meteor science, as well as it provides suitable environment for efficient collaboration and joint research studies.

Acknowledgment

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[5] http://airborne.seti.org
[6] http://www.hipersfera.hr

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