Meteors and meteorites spectra

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The main goal of our meteor spectroscopy project is to better understand the physical and chemical properties of meteoroids. Astrometric and spectral observations of real meteors are obtained via spectroscopic CCD video systems. Processed meteor data are inserted to the EDMOND database (European viDeo MeteOr Network Database) together with spectral information. The fully analyzed atmospheric trajectory, orbit and also spectra of a Leonid meteor/meteoroid captured in November 2015 are presented as an example. At the same time, our target is the systematization of spectroscopic emission lines for the comparative analysis of meteor spectra. Meteoroid plasma was simulated in a laboratory by laser ablation of meteorites samples using an (ArF) excimer laser and the LIDB (Laser Induced Dielectric Breakdown) in a low pressure atmosphere and various gases. The induced plasma emissions were simultaneously observed with the Echelle Spectrograph and the same CCD video spectral camera as used for real meteor registration. Measurements and analysis results for few selected meteorite samples are presented and discussed.

1 Introduction

Main goal in the meteors spectroscopy is to better understand the physical and chemical properties of meteoroids by using simultaneous video and spectral observations of meteors compared with meteoritic material laboratory spectra. Spectral observations of meteors are now obtained via fixed (at Valašské Meziříčí Observatory) and mobile spectroscopic CCTV systems. All records of meteors and processing data (orbital elements, speed of deceleration, etc.) are inserted to the EDMOND database (European viDeo MeteOr Network Database) together with spectral information (Kornoš et. al., 2014a). Another very valuable source of the physical and chemical properties of meteoroids are spectra taken by BRAMON (BRAzilian Meteor Observation Network). This network covers the southern hemisphere and is a source of information about the little-known southern hemisphere meteor showers.

Simultaneously, our target is the systematization of spectroscopic emission lines for the comparative analysis of meteor spectra. The solids will be irradiated using excimer and PALS lasers (Na, Ti, Mg, Al, Si, Fe, and Ca), their simple binary oxides, sulfides, minerals and real sample of meteorites. The LIDB (laser-induced dielectric breakdown) in a gas media representing the atmospheres (O_2, N_2, Ar and CO_2) will also be spectroscopically characterized. These spectra will be recorded in situ on the discharges and excimer laser ablations using a Fourier time resolved high resolution spectrometer Bruker, a high resolution Echelle spectrograph LLA and a CCD spectrograph Ocean Optics. Complying data will allow for not only qualitative determinations of the impacting body composition but also the assignment of spectral lines for products from the meteorite alterations and plasma interactions in atmosphere.

2 Equipment and data reduction

Spectrographs use a highly sensitive CCD video camera VE 6047 EF/OSD (spectrograph VM_N) and CMOS video cameras QHY5L-IIM (spectrographs VM_NW and VM_SW). The VE 6047 EF/OSD camera is equipped with a 1/3” CCD chip Sony ICX 673AKA with an effective resolution of 720 × 576 px, resolution of the VM_N spectrograph is 30,4 Å/px (Koukal et. al, 2015). The QHY5LII-M camera is equipped with a 1/3” CMOS chip Aptina MT9M034 with an effective resolution of 1280 × 960 px. The field of view is $80^o \times 60^o$ (spectrograph VM_SW) and $89^o \times 67^o$ (spectrograph VM_NW), these systems use fast Tamron megapixel lenses (f/1.0) with a variable focal length (3-8 mm). FOV and resolution of the CMOS chip enables the use of holographic diffraction grating with a density of 1000 lines/mm. In this configuration the spectrograph reaches a stellar limiting magnitude of $+4.5^m$, the faintest recorded meteors then have a relative magnitude of up to $+2.0^m$. The magnitude of meteors with measurable spectrum have to be at least $–2.0^m$.

The detection of meteors is done by UFOCapture software[1], and for the astrometric and photometric processing UFOAnalyzer software[2] (SonotaCo, 2009) is used. The resulting video is divided into individual

[1] http://sonotaco.com/soft/UFO2/help/english/index.html
[2] http://sonotaco.com/soft/download/UA2Manual_EN.pdf

images (frames), every image is subsequently a dark frame and flat field corrected with frames captured by the cameras VE 6047 EF/OSD and QHY5LII-M. Orbits of meteoroids in the solar system are calculated using the software UFOOrbit[3] (SonotaCo, 2009). The deceleration is derived from this software as an exponential fit of the actual speed of the meteor for each frame. Spectrograph calibration in the x-axis (wavelength) was performed using a calibration neon lamp. Calibration was performed as non-linear, using 6 multiplets of neon emission lines at wavelengths between 5852 and 7032 Å. The resulting basic spectrograph resolution was determined from 5 independent measurements at 9.7 Å/px (spectrograph VM_SW) and 10.8 Å/px (spectrograph VM_NW). The calibration of the emission line intensity (y-axis) was performed using a diagram of relative sensitivity CMOS Aptina MT9M034 at a wavelength between 3500 and 9000 Å *(Figure 1)*. For the identification of the emission wavelengths of the individual elements the revised tables were used (Moore, 1972).

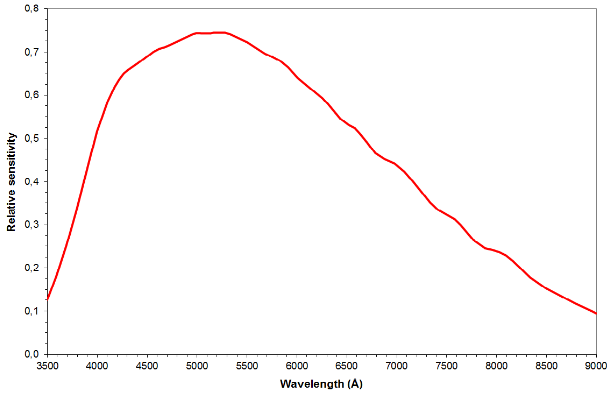

Figure 1 – Relative spectral sensitivity of CMOS chip Aptina MT9M034.

3 Comparative experiments with LIBS

The meteoroid plasma was simulated in our laboratory by a laser ablation of meteorites samples using a Lambda Physik (ArF) excimer laser. Comparative experiments with atmospheric gases have been performed using a Laser Induced Breakdown in gases and electric discharges. The emission spectra of plasma were simultaneously observed with the Echelle Spectrograph and the astronomical camera *(Figure 2, 3 and 8)*.

The laser emits ~10- ns pulses on a wavelength of 193 nm and an energy of 200 mJ. The Laser beam was focused using a calcium fluoride lens (focal length of 50 mm) on a solid target (a sample of a meteorite) attached on the XYZ rotation stage. The system is placed in a vacuum interaction chamber equipped with a collimator connected directly with a high resolution Echelle Spectrograph (ESA 4000, LLA Instruments GmbH, Germany). The spectrograph allows simultaneous measurement of complex spectra within the entire 200 – 780 nm UV / VIS – region with an effective resolution ranging from 0.005 nm (200 nm) to 0.019 nm (780 nm).

[3] http://sonotaco.com/soft/UO2/UO21Manual_EN.pdf

In our measurement, the spectrograph was set to trigger a 500 ns leaser pulse and to start the measurement with a delay of 4 µs with a gate open for 5 µs with the accumulation of 3500 counts and 30 accumulations of the signal. The positive column discharge was maintained by a high-voltage transistor switch applied between the stainless steel anode and the grounded cathode of the discharge tube (25 cm long with an inner diameter of 12 mm). The air plasma was cooled by water in the outer jacket of the cell. The voltage drop across the discharge was 1200 V, and the current was 250 mA.

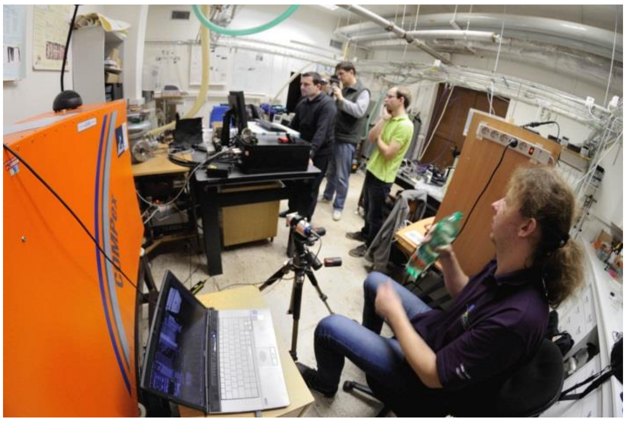

Figure 2 – Comparative spectroscopy in the laboratory of the J. Heyrovsky Institute of Physical Chemistry (the Czech Academy of Sciences) – the Echelle ESA 4000 high resolution spectrograph and the astronomical spectrograph QHY5LII-M.

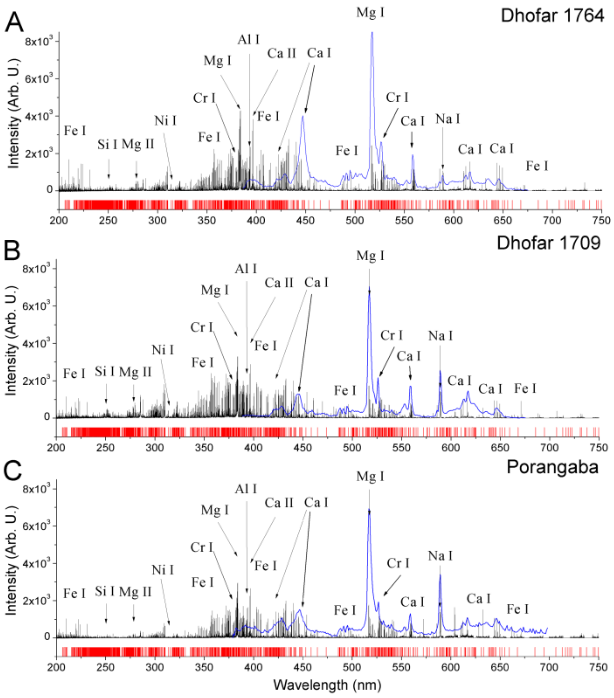

Figure 3 – Global survey on ablation emission spectra of all three samples of meteorites with assignment of the most prominent lines. The spectrum is also filled with a large number of Fe lines. Their positions are marked by red sticks below. In the figure, the spectrum recorded by the meteor spectrographic camera is imprinted in blue.

First of all, high resolution spectra of ablation plasma measured by Echelle spectrograph have been processed by the Calibration Free Method. The positions of the most prominent lines are depicted in *Figure 3*.

Figure 4 shows a Lorentzian fit of the Fe I 426.03 nm emission line in case of all the ablation spectra.

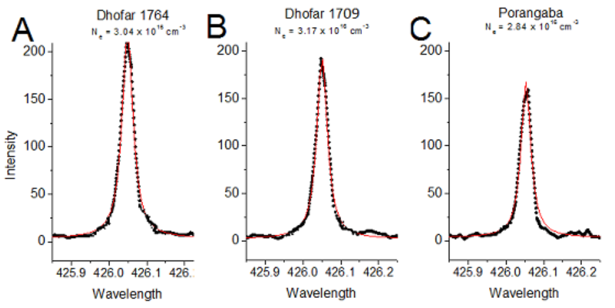

Figure 4 – Lorentzian fits of the Fe I emission line in all three ablation samples. For this clearly detectable line, Konjevič et al. estimated a line parameter of 0.11 A/nm. Using this values and FWHM of this line in all three measurements estimated using the fit, we obtain from the equation a mean electron density of 3.02×10^{16} cm^{-3}.

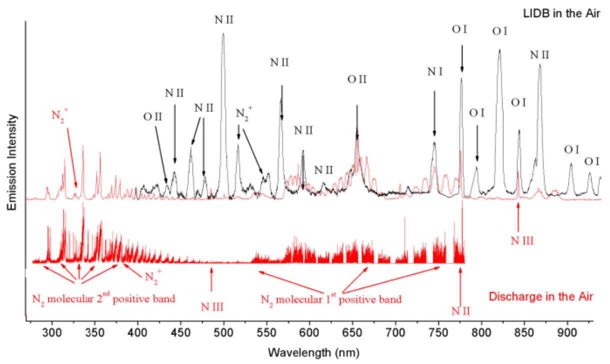

Figure 5 – Simulation of the meteoroid airglow by a laser induced breakdown in the air (black curve, low resolution spectrum) and an electric discharge (upper red low resolution and lower red high resolution spectra).

Spectra of laser induced breakdown and discharges in the air have been measured and assigned in order to identify using experimental methods the atmospheric bands featuring in the meteor spectra *(Figure 5)*. In the discharge, we detected strong emission spectrum of N_2 (C3Πu – B3Πg, around 330 nm, second positive band), B3Πg – A3Σu+, around 650 nm, the first positive band) and very weak emission of N_{2+} (B2Σu+ – X2Σg+, first negative band). The most prominent atomic species are ions O II, N II and weak lines of N III together with neutral N I and O I above 700 nm.

The temperature of the experimental high resolution spectra was estimated by using a Boltzmann and Saha-Boltzmann plot of the Fe I and Fe lines in the spectra. Every particular line of Fe was fitted by a Lorentz profile and the integral intensity was calculated *(Figure 6)*.

Using calibration free data processing we calculated concentrations C_S of the elements with the most prominent emission lines, i.e. Na, Mg, Fe, Ni, Cr, Al, Si and Ca *(Figure 7)*.

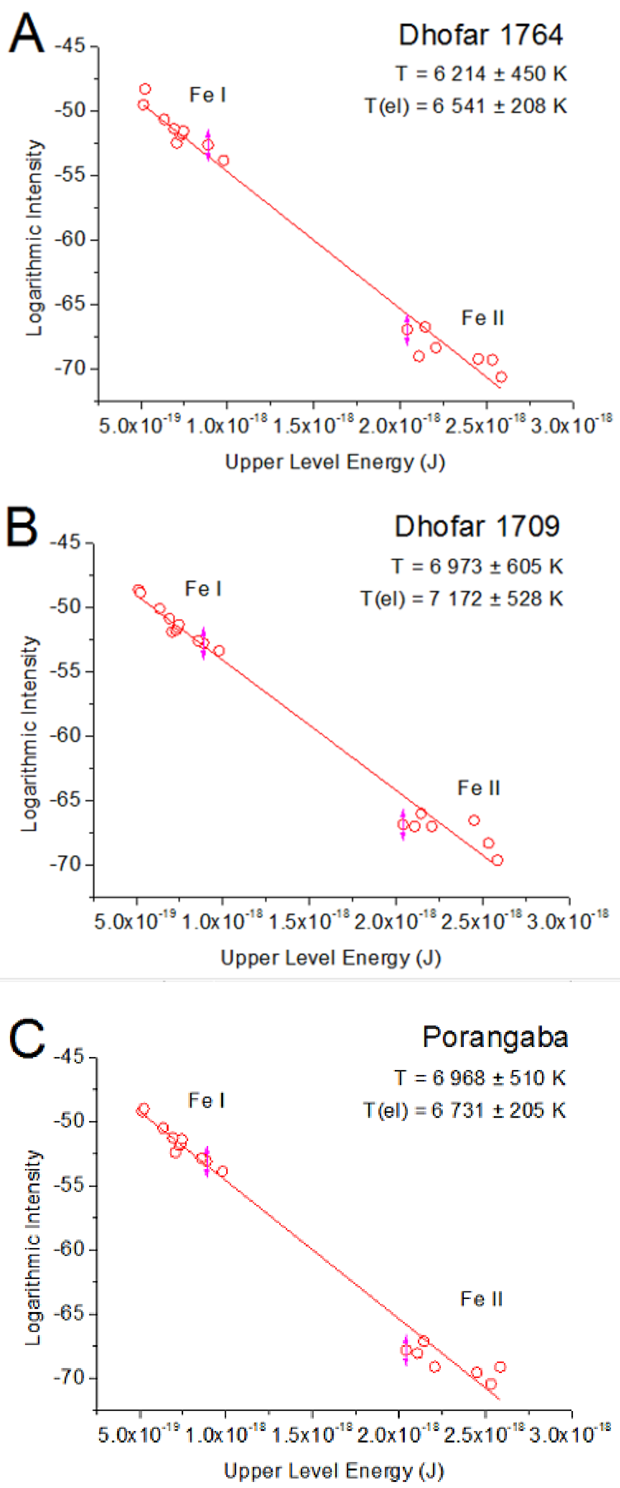

Figure 6 – The temperature of experimental high resolution spectra was estimated using a Boltzmann and Saha-Boltzmann plot of Fe I and Fe lines in the spectra. Every particular line of Fe was fitted by a Lorentz profile and the integral intensity was calculated. The slopes correspond to an electron temperature T_e = 8 566 ± 115 K.

	Sample	Electron temperature (eV)	Electron density (cm^{-3})	Fe/Mg	Na/Mg	Ca/Mg	Mg	Si/Mg	Al/Mg	Cr/Mg	Ni/Mg
A	Dhofar 1764	7172	3.18×10^{16}	1.22	0.003	0.11	1.00	0.82	0.19	0.02	0.06
B	Dhofar 1709	6541	3.03×10^{16}	1.83	0.020	0.17	1.00	1.15	0.34	0.05	0.09
C	Porangaba	6731	2.84×10^{16}	1.54	0.030	0.18	1.00	1.60	0.22	0.05	0.01

Figure 7 – Elemental abundances in all three samples of meteorites estimated using CF-LIBS technique.

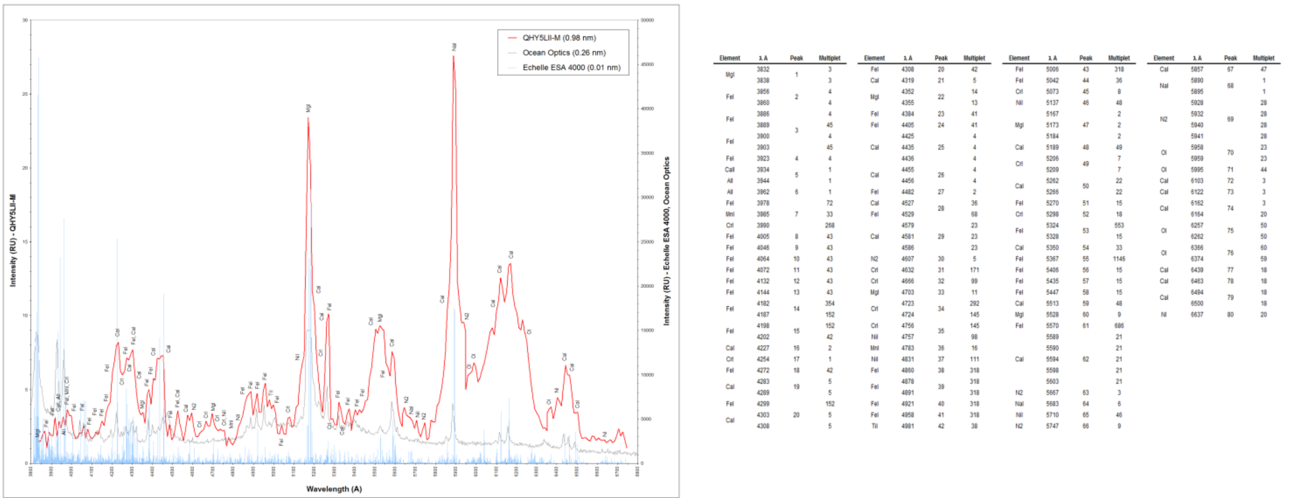

Figure 8 – The ablation emission spectrum of the Jiddat al Harasis meteorite (JAH 815) – the comparative measurement from the three sources. The measurement was performed using an Echelle ESA 4000 high resolution spectrograph, a CCD spectrograph Ocean Optics and an astronomical spectrograph QHY5LII-M with diffraction grating. The identified emission lines in the spectrum of the meteorite JAH 815 are listed in the table on the right.

4 Observations and results

Bolide 20151119_034504 (#013 LEO). The 2nd order is obvious in the recorded spectrum as well as the spectrum of the persistent trail *(Figure 9)*.

Figure 9 – Combined spectrum image of bolide 20151119_034504 - spectrograph VM_NW.

Overall 9 video frames of the bolide with 1st order spectrum were analyzed (spectrograph VM_NW) and a time resolved evolution of emission in the range from 3500 to 9000 Å was examined *(Figure 10)*.

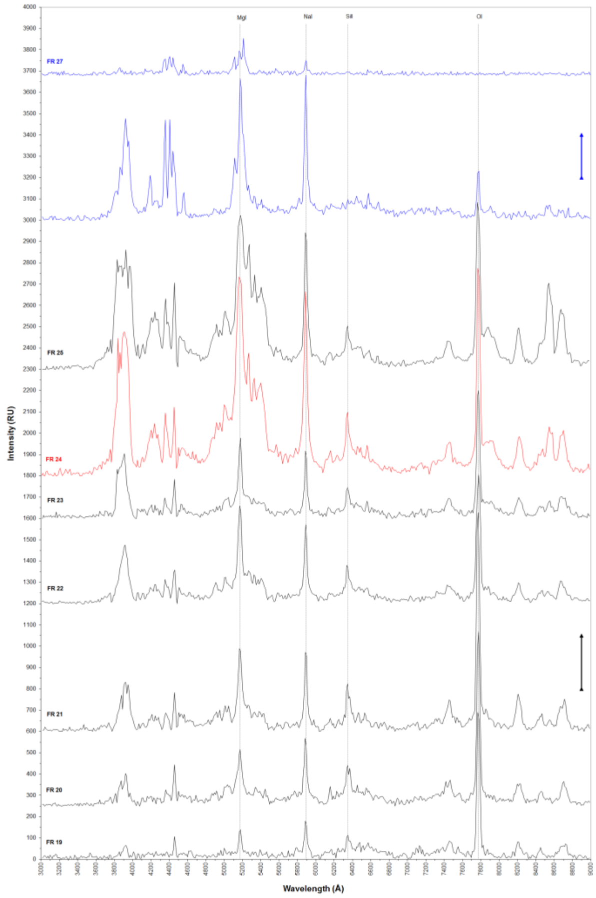

Figure 10 – Uncalibrated evolution of meteor spectrum in selected frames – 1st order, spectrum of the persistent trail is marked with blue, frame with the strongest emissions is marked with red.

Except of the dominant emissions of MgI-2, NaI-1 and CaII-1, the FeI-15 (5270, 5328 and 5405 Å) multiplet, MgI (3, 13 and 14 multiplets), CrI (1), CaI (4), FeI (318), and SiII (2) in combination with the emission line of the atmospheric elements (NI, OI, N_2 – 1st positive) identified in the 1st order *(Figure 11, 12)*.

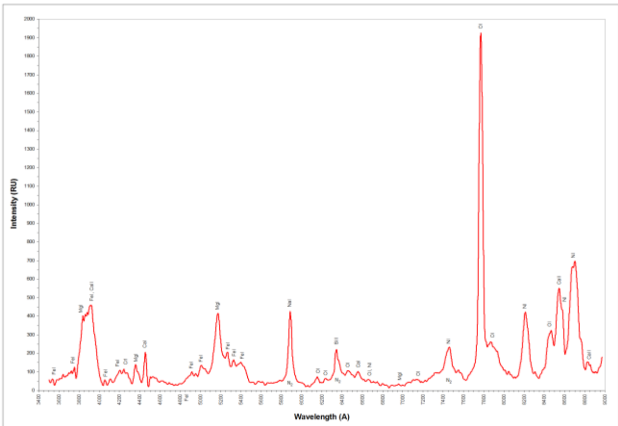

Figure 11 – Calibrated spectrum of bolide 20151119_034504 (1st order) in the range from 3500 to 9000 Å.

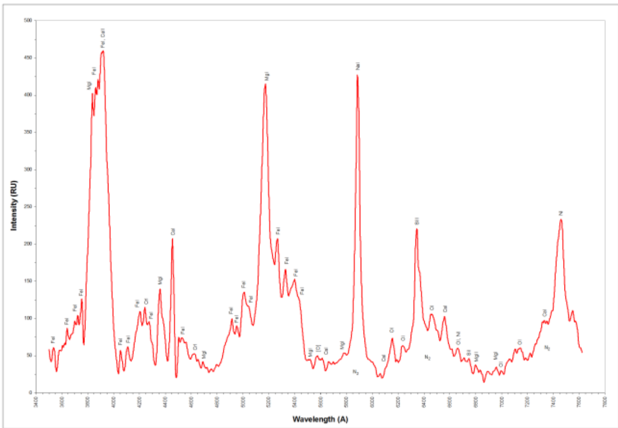

Figure 12 – Calibrated spectrum of bolide 20151119_034504 (1st order) in the range from 3500 to 7700 Å.

To calculation of the atmospheric path of the bolide and the orbit of the meteoroid in the Solar system the recordings from the stations Otrokovice, Zlín and Valašské Meziříčí (camera N) have been used. The projection of the beginning of the atmospheric path was located at coordinates N50.571° E17.603° near the village of Goszczowice (PL), the height of the bolide at this time was 126.6 kilometers above the Earth's surface. The end of the projection of the atmospheric path was located at coordinates N50.805° E17.292° near the village of Brylów (PL), the height of the bolide at this time was 74.7 kilometers above the Earth's surface, the bolide reached an absolute brightness of -8.6^m *(Figure 13)*.

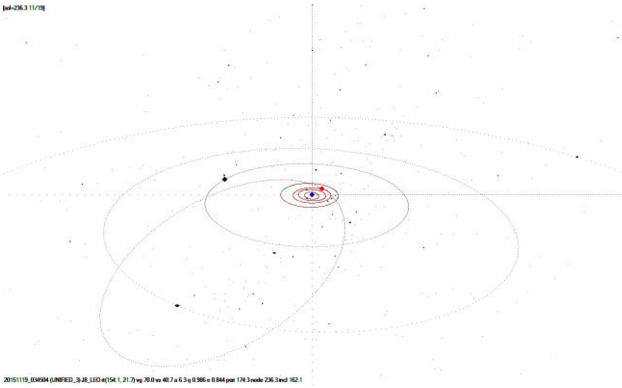

Figure 13 – Orbit of bolide 20151119_034504 (#013 LEO).

5 Summary and conclusion

The Observatory in Valašské Meziříčí has been successfully employed in the European Video Meteor Network (EDMONd), which consists of 265 CCD cameras across Europe. The main goal of this network is the determination of meteoroid trajectories. Additionally, we increase the scientific quality of the data by upgrading our EDMOND stations by spectrographs. For instance, recently (April 30, 2016), there are 74 spectra in the EDMOND database, of which 63 were recorded using spectroscopic systems in Valašské Meziříčí and 11 with mobile spectrographs *(Figure 14, 15)*.

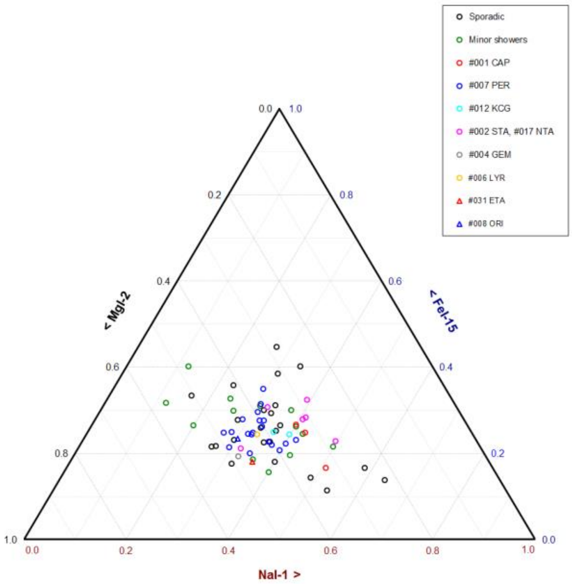

Figure 14 – Position of the parent shower of meteoroids in the ternary graph of the Mg I (2), Na I (1), and Fe I (15) multiplet relative intensities. Every shower is represented with a different symbol.

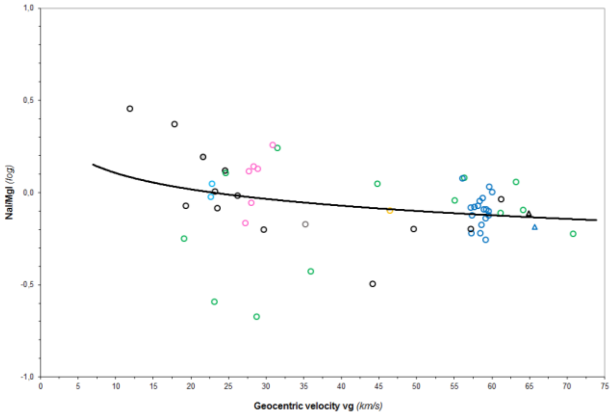

Figure 15 – Intensity ratio of the Na/Mg lines in meteor spectra as a function of the geocentric velocity.

Within the frame of the EDMOND database a new section of meteor spectra is gradually arising, which contains the combined observations taken with a mobile spectrograph in 2013, and observations collected since 2014 with spectrographs in Valašské Meziříčí. In the database there are also 19 meteor spectra (April 30, 2016) from BRAMON, which were recorded using the same spectroscopic system as the mobile spectrograph (Watec 902H2 Ultimate, diffraction grating 500 lines/mm).

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