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RNDr. Pavol Matlovič

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Physical properties of meteoroids

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Predkladateľ: **RNDr. Pavol Matlovič**
Oddelenie astronómie a astrofyziky
KAFZM, FMFI UK
Mlynská dolina F1
842 48 Bratislava

Školiteľ: **doc. RNDr. Juraj Tóth, PhD**

Študijný odbor: 4.1.7. Astronómia a 4.1.8. Astrofyzika
Študijný program: Astronómia a astrofyzika

Predseda odborovej komisie:

doc. RNDr. Jozef Klačka, PhD
Oddelenie astronómie a astrofyziky
KAFZM, FMFI UK
Mlynská dolina F1
842 48 Bratislava

Abstract

The aim of this work is to provide comprehensive study of spectral and physical properties of meteoroids from ground-based meteor observations. We utilize the observations of the All-Sky Meteor Orbit System (AMOS) network, specifically its Slovak part and emission spectra observations of the AMOS-Spec system at the Modra Observatory. Our analysis focuses on mid-sized meteoroids in the mm - m size range, observed as meteors of -1 to -14 magnitude. This work presents the widest survey of spectral and physical properties of this population of meteoroids. The obtained results are compared with previous studies of fainter meteors with the intention to reveal differences between the two populations.

First, we describe the developed pipeline for processing and reduction of meteor spectra. The atmospheric, orbital and structural parameters of corresponding meteoroids were processed and measured using established methods implemented in original AMOS software packages. Our analysis is based on 202 meteor spectra captured during 2013 - 2017 observations. The sample includes atmospheric, orbital and structural data for 146 multi-station meteors. Furthermore, we specifically focus on identified distinct spectral and dynamical groups.

Overall increase of Na/Mg ratio compared to the population of mm-sized meteoroids was detected, reflecting stronger effect of space weathering processes on smaller meteoroids. The preservation of volatiles in larger meteoroids is directly observed. The determined very low abundance of iron meteoroids in our sample and the discovery of a new spectral group - Fe rich meteors is discussed. Thermal processes causing Na depletion and implications for the altered meteoroid structure are described. We also present the first detailed analysis of Na enhanced and Na rich meteoroids. The influence of meteor speed on the detected Na/Mg ratio for slow meteors is discussed. Our study suggests that Na rich meteoroids are of chondritic composition and represent fragments of Apollo-type asteroids.

Numerous stream meteoroids were identified in our sample, enabling indirect probes into properties of their parent objects. Specifically, the spectral and structural properties of Taurids observed during the 2015 outburst are analyzed in detail. Our results imply inhomogeneous composition of the fragments of comet 2P/Encke and possible presence of carbonaceous bodies within the Taurid stream. Heterogeneity of several other streams including the Perseids of comet 109P/Swift-Tuttle, α-Capricornids of 169P/NEAT and sungrazing δ-Aquarids of 96P/Machholz is also described.

Finally, we describe the initiated new project focused on linking the spectral classification of meteors from ground-based observations with high-resolution Echelle spectra of simulated ablation of known meteorites in high-enthalpy plasma wind tunnel. The experiment aims to improve our abilities to recognize meteoroid composition from meteor observations.

Keywords: meteor, meteoroid, asteroid, comet, spectroscopy, composition

Abstrakt

Cieľom práce je komplexné štúdium spektrálnych a fyzikálnych vlastností meteoroidov na základe diaľkových pozorovaní meteorov. Využívame pozorovania siete systémov All-Sky Meteor Orbit System (AMOS), konkrétne jej slovenskú časť a emisné spektrá získané systémom AMOS-Spec na observatóriu v Modre. V analýze sa zameriavame na meteoroidy v rozmedzí veľkostí mm - m, pozorované ako meteory -2 až -14 magnitúdy. Práca predstavuje doteraz najväčšiu prehliadku spektrálnych a fyzikálnych vlastností tejto populácie meteoroidov. Získané výsledky sú porovnané s predošlými štúdiami slabších meteorov s cieľom odhaliť rozdiely medzi týmito dvoma populáciami.

Najprv popisujeme vyvinutú metodológiu na spracovanie a redukciu spektier meteorov. Atmosférické, dráhové a štrukturálne parametre korešpondujúcich meteoroidov boli spracované a zmerané použitím zaužívaných metód implementovaných vo vlastných software balíkoch AMOS. Naša analýza je založená na 202 spektrách meteorov zachytených počas pozorovaní v rokoch 2013 - 2017. Vzorka obsahuje atmosférické, dráhové a štrukturálne dáta k 146 viac-staničným prípadom. Ďalej sa špecificky venujeme identifikovaným spektrálnym a dynamickým skupinám.

Detegovaný bol celkový nárast pomeru Na/Mg v porovnaní s populáciou milimetrových meteoroidov, ktorý prejavuje slabší vplyv efektov vesmírneho zvetrávania na veľké meteoroidy. Výsledok poukazuje na prezerváciu prchavých látok vo väčších meteoroidoch. V práci popisujeme určený veľmi nízky podiel čisto železných meteoroidov v našej vzorke a poukazujeme na objav novej spektrálnej skupiny obohatenej na železo. Popisujeme tepelné procesy spôsobujúce ochudobnenie na sodík a implikácie pre zmenu štruktúry meteoroidov. V práci tiež predstavujeme prvú detailnú analýzu meteoroidov skupiny Na enhanced a Na rich. Poukazujeme na vplyv rýchlosti meteorov na detegovaný pomer intenzít Na/Mg najmä pri pomalých meteoroch. Na základe našich výsledkov predpokladáme, že Na rich meteoroidy sú chondtritického zloženia a predstavujú fragmenty asteroidov typu Apollo.

Vo vzorke sme identifikovali viacero meteoroidných prúdov, ktoré umožňujú nepriame sondy do vlastností ich materských telies. Detailne analyzujeme spektrálne a štrukturálne vlastnosti Tauríd pozorovaných počas zvýšenej aktivity v roku 2015. Naše výsledky implikujú nehomogénne zloženie fragmentov kométy 2P/Encke a možnú prítomnosť uhlíkatých materiálov v komplexe Tauríd. Preukázaná je tiež heterogénnosť ďalších prúdov vrátane Perzeíd z kométy 109P/Swift-Tuttle, α-Capricorníd z 169P/NEAT a δ-Aquaríd z 96P/Machholz.

Na záver popisujeme iniciovaný projekt zameraný na prepojenie spektrálnej klasifikácie meteorov s Echelle spektrami vo vysokom rozlíšení simulovanej ablácie známych meteoritov vo vysoko entalpickom plazmovom veternom tuneli. Cieľom experimentu je zlepšiť naše schopnosti rozpoznať meteoroidné zloženie z pozorovaní meteorov.

Kľúčové slová: meteor, meteoroid, asteroid, kométa, spektroskopia, zloženie

Preface and motivation

Studying the Solar System, as our home planetary neighborhood, the outlook for the first space travels, and the only recognized source of life has always been one of the main interests of astronomy and science in general. Despite the significant progress in our understanding of how the Solar System was formed, what bodies constitute it, and what mechanisms influence their motion, there are still numerous unanswered questions regarding the complex nature of our planetary system.

Many of the key information we have about the Solar System come from the studies of the oldest remnants left over from the planetary formation in the early protosolar disk - asteroids, comets, and meteoroids. On one side, these bodies can reveal the processes and conditions occurring in the early stages of the Solar System. On the other, they can give rise to the dangers of catastrophic impacts, which have subjected our planet numerous times in the history. In each case, they are the topic of high scientific interest. The studies of asteroids and comets are however often complicated by the small size and low albedo of these bodies. Usually only limited amount of information can be obtained from direct observations. Meteor observations during the interaction of meteoroids with the Earth's atmosphere allow us to study small Solar System bodies, which would otherwise remain undetected.

Recently, meteor astronomy has been gaining popularity among professional and amateur astronomers, due to the arising possibilities of using inexpensive technologies, particularly sensitive CCD cameras to effectively observe meteors and provide valuable scientific data. Most of these efforts are focused on studying the activities of meteor showers, determining original heliocentric meteoroid orbits or detecting potential meteorite impacts from the brightest bolides. The research focused on physical and compositional properties of meteoroids is still rather limited. The main goal of our work is to provide complex characterization of mm-m sized meteoroids based on a combination of spectral, orbital and structural properties derived from video meteor observations. This data set will allow us to study the nature and origin of sporadic meteoroids and meteoroid streams in more detail. Additionally, it can provide implications for their parent comets or asteroids.

Methods and observations

The meteor data analyzed in this work come from observations of the All-sky Meteor Orbit System (AMOS) network developed and operated by the Faculty of Mathematics, Physics and Informatics (FMPI) of the Comenius University in Bratislava. The network consists globally of 11 standard AMOS systems and 5 spectral systems AMOS-Spec. Standard AMOS systems provide continuous all-sky detection of meteors and are used to determine the atmospheric trajectory and original heliocentric orbit of observed meteoroids. The system was originally developed in 2007 and established within the Slovak Video Meteor Network in 2009.

The primary goal of this work is to analyze meteor spectra collected by the original AMOS-Spec system at AGO Modra during 2013-2017 routine observations. Dynamical analysis of the selected meteors is enabled by multi-station observations from four standard AMOS stations in Slovakia. In specific cases, additional individual observations from other AMOS-Spec stations were used. The presented spectra were detected in span of the entire year and include sporadic meteors as well as meteors from known meteoroids streams. All spectra with S/N > 4 were selected for our analysis.

The image processing and reduction of spectra analyzed in this work was performed according to the procedure described in [8]. In the first step, all spectral recordings are corrected for dark frame and flat-field images, and have the star background image subtracted to reduce noise and other sources of illumination. The all-sky geometry of the AMOS-Spec lenses causes slight curvature of events captured near the edge of the FOV. Each spectrum is therefore manually scanned using the ImageJ[1] program on all individual frames (heights) with spectrum signal.

The spectral reduction is performed within several developed MATLAB codes. All spectra are first scaled based on recognized spectral lines and polynomial adjust of 2nd or higher degree. Usually, the lines of Mg I – 2 (518.2 nm), Na I – 1 (589.2 nm), O I – 1 (777.4 nm), and Fe I – 41 (438.4 nm) are used for the scaling, providing optimal fit for the identification of other lines. The wavelength scale is later fine-tuned during the fitting procedure. Each spectrum is fitted with a simple model accounting for all significant contributions to the observed meteor radiation in the visible spectrum. The continuum level was fitted by a Planck curve at given temperature. The characteristic temperature of the Planck curve was modified depending on the speed and brightness of a meteor. In most cases, the continuum was well fitted by Planck curve at 3000 - 4000 K.

Furthermore, each spectrum was fitted with the most significant spectral lines (low temperature,

[1] https://imagej.nih.gov/ij/

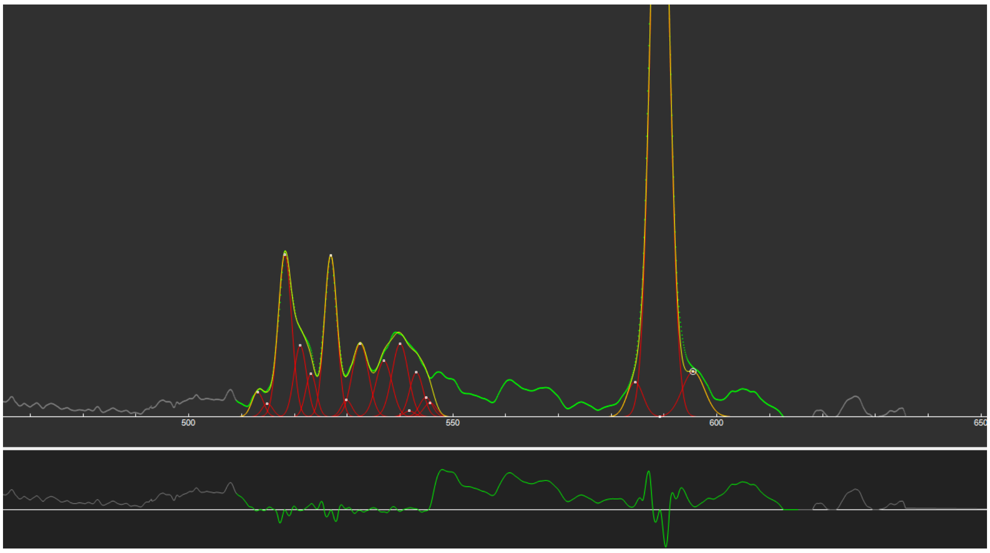

Figure 1: Fit of the synthetic spectrum (yellow) on measured calibrated meteor spectrum (green) as a convolution of the main emission contributions (red) in the 510-600 nm region. Residuals of the fit can be seen below the spectrum.

high temperature, atmospheric, and wake lines) in meteors using the Fityk software [16][2]. The initial positions and typical relative intensities of fitted lines and bands were taken from [1], adjusted and supplemented to accommodate the properties of the AMOS-Spec system. The modeled lines were used to create a synthetic spectrum, which was then compared and adjusted to fit the measured and calibrated meteor spectrum. The fitting procedure follows the Levenberg–Marquardt algorithm, also known as the damped least-squares method. The modeled lines have Gaussian profiles with full width at half maximum (FWHM) typically 3 nm. Moreover, the most notable molecular N_2 bands of the first positive system present in the meteor spectra were fitted using the positions and intensities taken from [1], and adjusted for our spectra. The Gaussian width of these bands was assumed to be 10 nm. Finally, atmospheric emission lines of O I, N I and most notable molecular N_2 bands were fitted in the synthetic spectrum depending on the meteor speed and subtracted.

In this work, we focus on the main meteor multiplets of Mg I – 2, Na I – 1, and Fe I – 15 which form the basis of the spectral classification of meteors. The intensities of these multiplets were measured in the fitted synthetic spectrum subtracted of the continuous radiation and atmospheric emission, and the resulting ratios applied for the spectral classification. The modeled contributions of all recognized lines of the Fe I - 15 multiplet were summed.

Furthermore, atmospheric, orbital and structural properties of meteors were processed and measured based on series of procedures implemented in the AMOS pipeline. The specific methodology is described in detail in the dissertation.

[2]http://fityk.nieto.pl/

Survey of mm-m sized meteoroids

The core of this work is focused on an analysis of 202 meteor spectra captured by the AMOS-Spec system during time period between December 2013 and August 2017. The sample includes meteors of -1 to -14 mag, which corresponds to meteoroids of mm to m in size. This way, we are able to provide spectral study of the population of mid-sized meteoroids, which complements existing works focused on fainter meteors corresponding to mm-sized bodies [1,10], and bright fireballs often caused by over m large, potentially meteorite dropping meteoroids [3,7].

The survey of spectral properties of selected meteors is performed by means of spectral classification of meteors [1]. While this method was developed for a study of fainter meteors, it is compatible with the specifics of the AMOS-Spec system. Fundamentally, the main condition for such application is high instrumental spectral sensitivity in the studied 500-600 nm region and sufficient resolution to distinguish and measure individual multiplets of Na I - 1, Mg I - 2 and Fe I - 15. This is well satisfied by the AMOS-Spec. However, we do not assume that the results of our population will directly correspond to the survey of fainter meteors published by [1] and [15]. We expect that the physical conditions (size/brightness) of different meteoroid populations to some degree affect the observed spectra. One of the goals of this work is to identify and describe the spectral differences between these populations.

Spectral classification

The spectral classification of our sample is on Fig. 2. Out of the 202 measured meteors, 145 have been identified as normal type. Similarly to previous studies of mm-sized meteoroids [1, 15], the majority of mm-m sized meteoroids spectra are positioned in the middle part of the ternary diagram. Normal type meteors are defined as those lying close to the expected position for chondritic bodies, as modelled by [1]. These theoretical values and resulting mean curve were determined assuming chondritic composition and range of temperatures, densities and sizes of the radiating plasma. This curve might not equally represent the characteristic chondritic area within our sample of meteors created typically by larger meteoroids. It is likely that the conditions of mean temperature and size of the radiating plasma are shifted in our population. While no theoretical simulation was performed, the characteristic positions of normal type meteors were simply inferred from the densest part of the distribution on Fig. 2.

We observe overall increase of the Na/Mg ratio in our population of meteoroids compared to

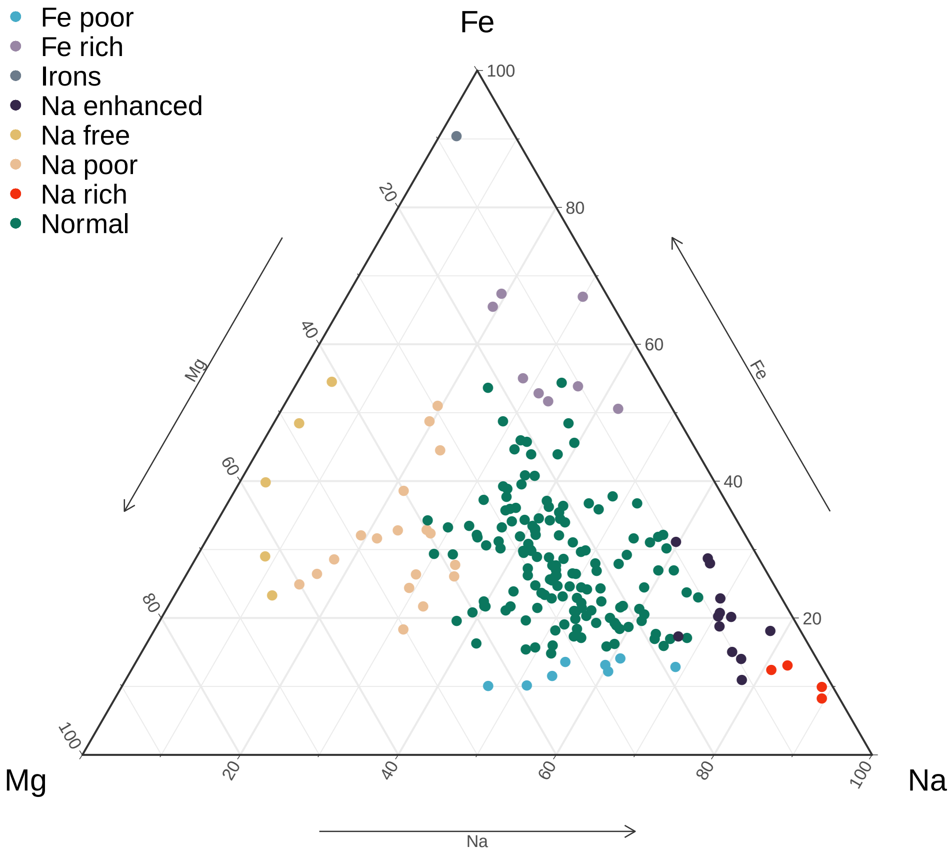

Figure 2: Ternary diagram displaying the spectral classification of 202 meteors observed by the AMOS-Spec system during 2013-2017. The displayed meteors cover magnitude range from -1 to -14, corresponding to meteoroids of mm-m in size.

smaller meteoroids studied by [1] The shift of the spectral classification among two size populations of meteoroids can be seen on Fig. 3. Similar comparison can be made with the results of [15] focused on similar size population and showing equivalent distributions.

We suggest that the observed shift reflects the compositional variations between the two size populations of meteoroids. Sodium is a volatile element, which can be easily depleted from small bodies by space weathering processes. These effects mainly concern exposure solar radiation (and specifically thermal desorption during close approaches to Sun) and probably the solar wind and cosmic ray irradiation. Depending on the composition and time of exposure, these processes affect mainly the outer layers of interplanetary bodies. For smaller meteoroids, the space weathering processes likely cause more effective volatile depletion within the meteoroid volume. In larger meteoroids studied in our sample, volatiles can be partially depleted from the outer layers but can remain intact below the surface. The effect of Na depletion might not only concern the space weathering processes before the atmospheric entry. The preheating of the meteoroid in Earth's atmosphere could cause some degree of Na depletion before the meteor spectrum can be observed. The preheating would also more significantly affect smaller meteoroids. Some degree of Na enhancement in 13 larger meteoroids was already noted by [14]. The effect is also confirmed by the apparent differences between the overall number of Na poor and Na free meteors observed in our sample compared to [1]. Only 11.5% of our sample represents these classes, compared to 34% among mm-sized meteoroids.

The second most notable difference between the two meteoroid populations is the apparent lack of iron bodies in our sample. Meteor spectra dominated by Fe lines are assumed to come from meteoroids composed mainly of iron-nickel alloy [1,4]. Only one iron meteor has been identified in our sample, compared to approximately 14% among fainter meteors of [1]. Similarly, 10% of iron meteoroids were detected by [15] among comparable size population. This is unexpectedly large ratio considering the statistics from known meteorite falls. According to the Meteoritical Bulletin Database[3], only 4.4% of all found meteorites were identified as irons. This sample only concerns strong bodies, which are able withstand the atmospheric flight. The ratio of iron bodies in interplanetary space would be expected even lower. According to the results of [1], irons are dominant among meteoroids on asteroidal orbits. This is in strong contrast to our results, suggesting most asteroidal meteoroids in cm-m size range are chondritic.

[4] pointed out the specific ablation process of small (0.7 - 2.1 mm) iron meteoroids. The light curves typically exhibit very steep initial increase of brightness and a gradual decrease. Similar light curves have been detected among small refractory meteoroids composed of iron-nickel alloy or iron sulfide grains. According to [4] and [5], the ablation of these meteoroids is in the form of droplets released from a liquid layer at the meteoroid surface. [1] speculated that if the meteoroid consists of metallic iron with high thermal conductivity, the whole millimeter sized meteoroid could be melted completely before the vaporization. It is possible that the population of small mm-sized meteoroids includes higher number of individual iron grains, which are not common as separate bodies among cm - m sized meteoroids. Further investigation is necessary to reveal the processes by which the population of small iron meteoroids is formed. In future, we plan to study the abundance of iron meteoroids observed from high resolution spectrographs from Canary Islands, Chile and Hawaii.

While to abundance of iron bodies in our sample is very low, we have detected several meteors positioned between the normal type and iron class. In this work, we introduce new spectral class of Fe rich meteors. We define Fe rich meteors as having significantly higher Fe/Mg intensity ratio compared to normal type meteors, while still notable presence of both Na I and Mg I. These meteors are positioned in the upper part of the ternary diagram (Fig. 2). No meteors were detected in this part of the ternary diagram in the surveys of fainter meteors. In some cases, the intensity of Fe can be overestimated in meteors during bright flares. The pixel saturation and optical thickness of the radiating plasma can cause apparent increase of the Mg/Fe ratio. To reduce this effect, frames with notably saturated spectra were neglected from the line intensity measurements. Furthermore, Fe/Mg ratio was specifically studied in non-saturated frames before and after meteor flares, and the relative intensity of the Fe I - 41 multiplet in the 438 - 441 nm region was evaluated to identify Fe rich meteors.

[3] https://www.lpi.usra.edu/meteor/

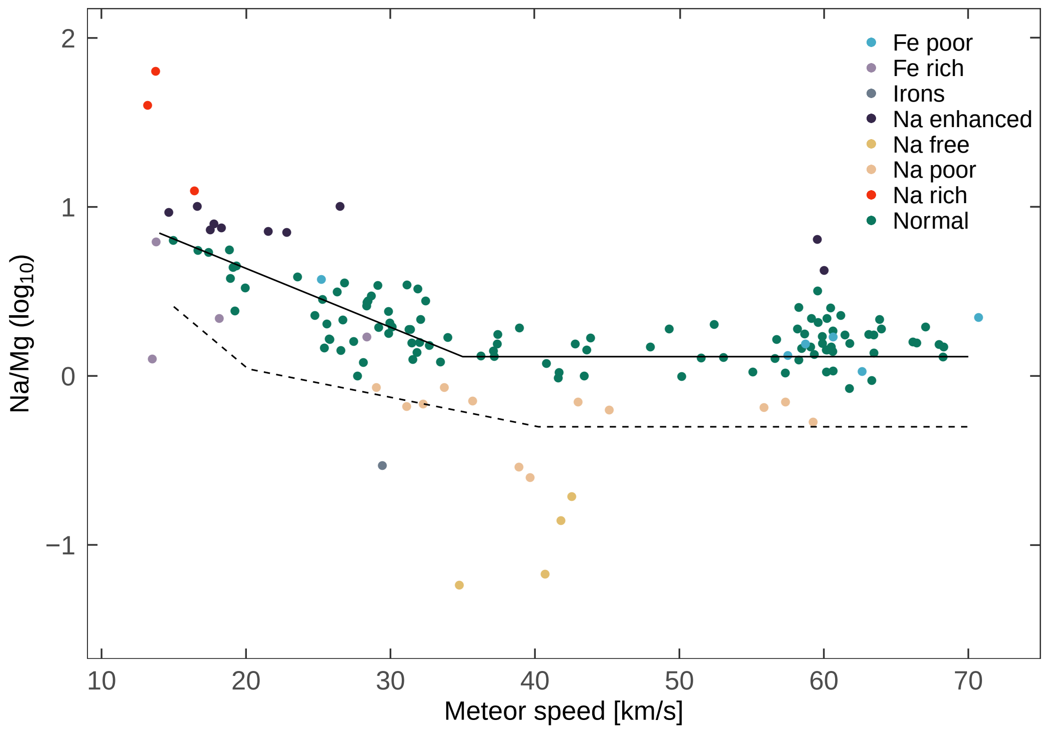

Figure 3: The observed Na/Mg intensity ratio as a function of meteor speed. The solid line represents an approximate fit of meteors classified as normal. The dashed line represents fit of normal type meteors from [1] dealing with mm-sized meteoroid population.

Meteor orbits

In this section, we focused on combining the detected spectra with determined atmospheric trajectories and heliocentric orbits. The full results are compiled in the dissertation.

Most importantly, we note that the dependence of Na/Mg intensity ratio on meteor speed (Fig. 3) shows increase of mean Na/Mg values compared to smaller meteoroids studied by [1]. The Na/Mg intensity ratio is dependent on meteor speed (temperature) as a result of the low excitation of Na I line (2.1 eV) compared to Mg I (5.1 eV). Among mm sized particles, this effect is observed for meteor speeds below 40 km s^{-1}. Similar functionality is detected in our sample of larger meteoroids, with the threshold value of meteor speed shifted to 30-35 km s^{-1} (Fig. 3). This breaking point also corresponds to the recent results of [15]. The effect of meteor speed on observed spectrum, specifically the Na line was further analyzed in detail in the dissertation.

Tisserand parameters with respect to Jupiter was used to classify the orbital origin of meteoroids, distinguishing Halley type orbits for bodies originating in the Oort cloud ($T_J < 2$), Jupiter-family orbits for meteoroids from Kuiper belt ($2 < T_J < 3$) and asteroidal orbits for bodies from the main Asteroid belt ($T_J > 3$). Overall 61 meteoroids were found on Halley-type orbits, 42 meteoroids on Jupiter-family type orbits and 28 meteoroids on asteroidal orbits. To some degree, the orbital origin of meteoroids reflects on the detected spectral properties of meteors. Fig. 4 shows increase of Fe/Mg intensity ratio for meteoroids originating in the main asteroid belt and decrease of Fe/Mg intensity ratio for meteoroids on Halley-type orbits. We assume that the majority of meteoroids on orbits with $T_J > 3$ (with the main exception of several meteoroids from the Taurid stream) are of asteroidal origin. These chondritic bodies have in general larger iron content compared to mostly cometary meteoroids on Halley-type orbits. The distinction between Jupiter-family and Halley-type meteoroids in the characteristic Fe/Mg ratios is less apparent, though on average also present. The Na/Mg ratio apparently increases for meteoroids on asteroidal orbits (Fig. 4). This effect is however mainly caused by the increase of Na/Mg ratio in slower meteors (Fig. 3). All of the meteors with $T_J > 3$ have initial velocities $v_i < 35$ km s^{-1}.

Our work also includes detailed analysis of several major and minor meteoroid streams, enablining indirect studies of their parent objects. The orbital similarity was in specific cases evaluated using the Southworth-Hawkins criterion [11].

The most represented meteoroid stream in our sample are the Perseids originating in comet 109P/Swift–Tuttle with 19 identified samples. Several more Perseid spectra were observed, but with only recognizable atmospheric emission lines. Most Perseid meteors are positioned in the middle of the ternary diagram with normal type spectra close to the expected chondritic ratios of Na/Mg/Fe. Relatively large variation of Fe content is observed, between 10 to 40% in the ternary ratios. Four Fe poor Perseids are observed. The Na/Mg ratios for Perseids are within the expected normal type region, with one exception identified as Na enhanced. One Perseid meteor was classified as Na poor, pointing out the possible effect of cosmic ray irradiation causing volatile depletion on Halley-type orbits.

Among other Halley-type showers, we have detected pair of meteoroids from σ-Hydrids and Lyrids and three 49 Andromedids, showing relatively heterogeneous spectral properties. Heterogeneity of meteoroids from one parent object seems to be quite common, as we previously noted in our study of Taurid meteoroids [8]. Some degree of Na enhancement is detected in one Lyrid and 49 Andromedid, while one σ-Hydrid is classified and Na poor as a result of its small perihelion distance. Our sample also includes one Orionid meteoroid with relatively high Fe intensity. The meteor spectrum was observed during meteor flare, which could cause some degree of Fe intensity overestimation due to saturation and optical thickness of the radiating plasma. Even considering these effects, the observed Fe intensity is unusually high for a cometary body originating in comet 1P/Halley.

Besides Taurids, ecliptical showers were most represented in our sample by the κ-Cygnids (6 meteoroids) and α-Capricornids (4 meteoroids). κ-Cygnids are spectrally similar to the Taurids, showing relatively similar Na content and higher variations of Fe intensity. The α-Capricornids show two distinct types of spectra. The two types of α-Capricornids exhibited very distinct light curves. The first type shows spectra with increased Fe intensity observed during bright flares associated with sudden disruption. The second type shows Na enhancement and lower Fe content with smooth light curves without flares. We believe that these variations reflect the structural heterogeneity of the stream, specifically relating high porosity in some samples, causing distinct release of volatiles.

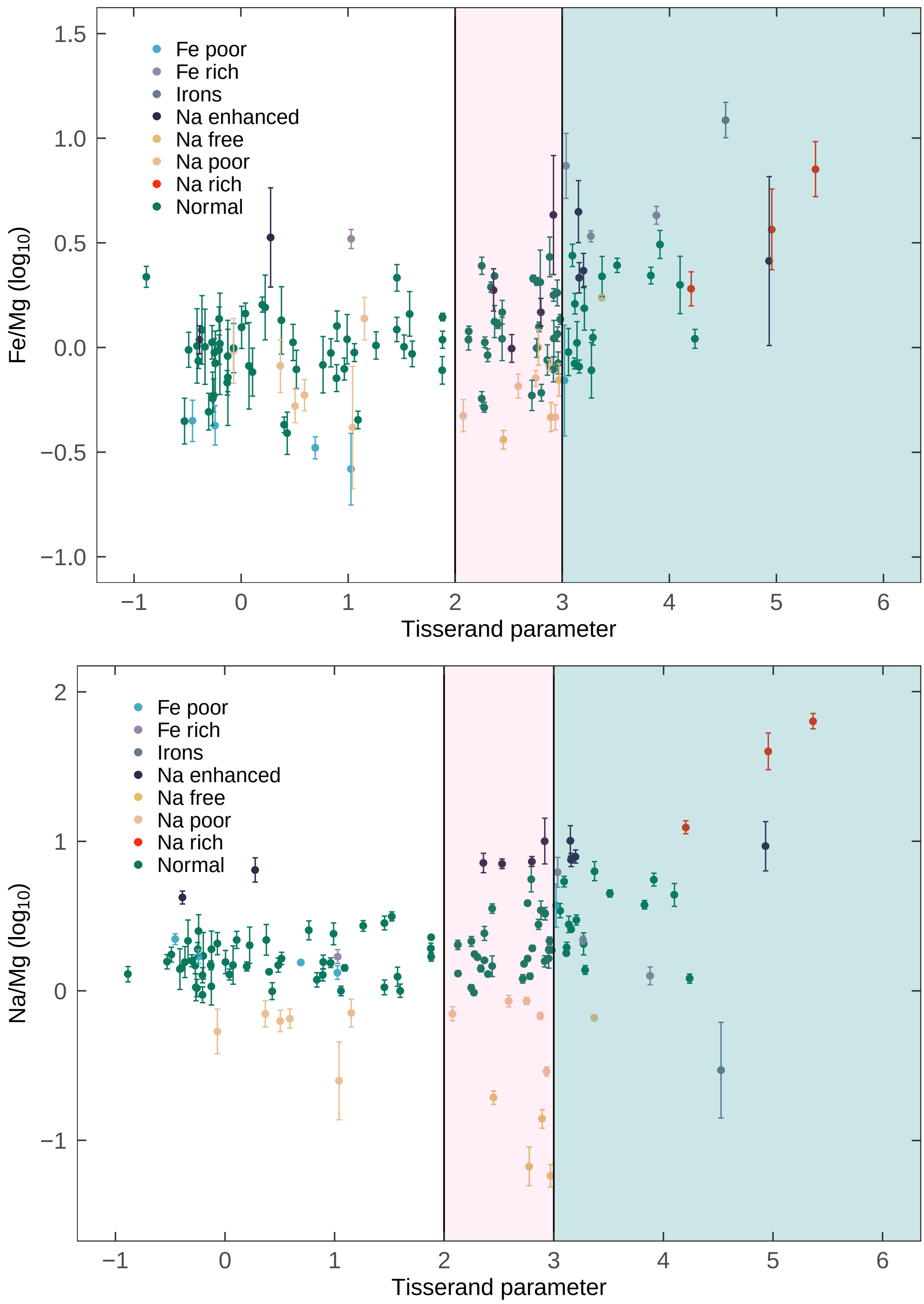

Figure 4: The observed Fe/Mg intensity ratio (upper) and Na/Mg intensity ratio (lower) as a function of the Tisserand parameter relative to Jupiter. The colored areas represent asteroidal (green) and Jupiter-family type (red) orbits.

Structure

Within the structural analyses, we mainly focused on the determination of material strength properties based on empirical parameters K_B and P_E [2] differentiating between the softest cometary materials

(D/IIIB), standard cometary materials (C/IIIA), dense cometary bodies (B), carbonaceous bodies (A/II) and ordinary chondritic bodies (ast/I). In the dissertation, further analysis based on determined grain densities and dynamic pressures for individual cases is provided.

The corresponding material classification for all meteoroids is displayed on Fig. 5. No clear preference of meteor magnitudes is observed in the K_B classification. The P_E distribution shows that mostly bright fireballs are found among the most fragile IIIB meteoroids, including seven fireballs brighter than -8 mag. The meteor magnitude does not always fully reflect on original meteoroid mass. For example, the strong Na rich meteoroids are of moderate magnitudes, even though we estimated relatively high photometric mass.

Fig. 5 shows that Na rich, Na free and Na poor meteoroids are on average composed of the strongest material. Numerous strong, chondritic materials are also identified among normal type meteors, though none of them are found in the ordinary chondrites group (ast) in the K_B classification. High material strength K_B is also detected in Fe rich meteoroids, though the P_E values are scattered and generally low. This behavior could reflect the enhanced iron content, as the ablation of iron meteoroids is atypical with relatively short light curves and moderate terminal heights. The same pattern is observed in the only iron meteoroid in our sample which exhibits high material strength at the beginning of ablation (ast), but dissipates quite early (IIIA). The lowest material strength is on average found in Fe poor meteoroids, similarly to the previous results for smaller meteoroids [15].

Our results also demonstrate the correlation between the determined material properties and meteor orbits (Fig. 5). Meteoroids originating in the main asteroid belt or from NEO orbits ($T_J > 3$) are on average of higher material strength, most often characteristic for carbonaceous and ordinary chondrites. Few fragile meteoroids were also found on asteroidal orbits, mainly including shower meteors of the Taurids and α-Capricornids. This population represents fragments of short-period comets, which are underabundant compared to asteroidal bodies in this region, but produce larger amount of dust particles. In case of the Taurids, there are hints that the stream also contains chondritic debris from nearby asteroids, though this not clearly apparent in our data.

The range of materials detected on the Jupiter-family orbits is wider and includes asteroidal and cometary meteoroids. On average, the majority of meteoroids in this region are defined by the cometary and carbonaceous material strengths (C-A/IIIA-II). Several meteoroids with material properties similar to ordinary chondrites are also present, in large part represented by Na poor and Na free spectra. In this case, the hardening of material during close approaches to Sun associated with the release of volatiles is responsible for the detected high material strengths. The K_B values show no meteoroids composed of the softest cometary material (type D) present on Jupiter-family orbits. Our results also suggest that meteoroids from Halley-type orbits do not contain ordinary chondrites (ast/I type). Overall, the meteoroids on Halley-type orbits are mainly of typically fragile structure, including several meteoroids of the softest cometary material (D/IIIB). The most fragile structure was typically found among brighter fireballs and included several stream meteoroids, mainly the Perseids, κ-Cygnids and α-Capricornids.

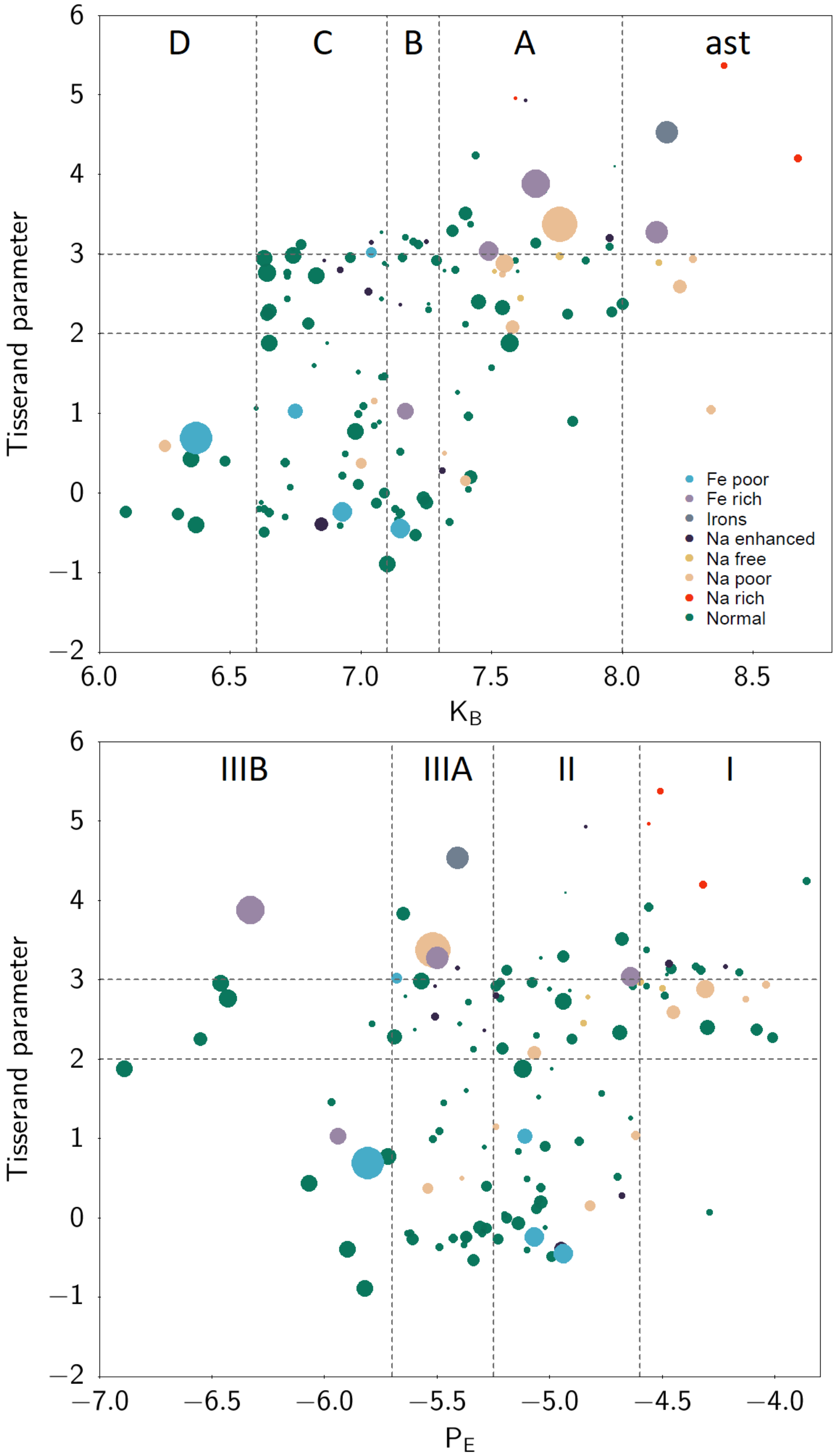

Figure 5: Material strength classification of all meteoroids observed by multiple stations based on the K_B (upper) and P_E (lower) parameter as a function of the Tisserand parameter. Sizes of meteoroid marks reflect relative meteor magnitudes. Color coding differentiates between the determined meteor spectral classes.

Other results

Besides the general results from the wide survey of mm-m sized meteoroids, we further focused on detailed analyses of specific spectral and dynamical groups detected in our sample. Here we present compilation of most notable results from these studies:

- Na poor and Na free bodies were identified in lower abundance among cm-m sized meteoroids compared to mm-sized bodies. The difference reflects the preservation of volatiles in larger meteoroids. Thermal desorption was identified the most common process causing Na loss, confirmed by the found dependency of Na/Mg ratio on perihelion distance (q). Furthermore, we found that detected Na depletion is correlated with the dynamic age of a meteoroid. The loss of volatiles during close perihelion approaches was found to be linked with hardening of the meteoroid material, as presented by the detected high material strengths of Na poor and Na free samples (Fig. 5).

- We reported the discovery of a new spectral type of Fe rich meteors. The meteors have spectra with Fe intensity between pure irons and chondritic meteoroids and originate on asteroidal orbits. We suggest that this group may contain iron enhanced (H-type) chondrites and bodies similar to stony-iron meteorites.

- The orbital and structural properties of Na rich and Na enhanced meteoroids were for the first time analyzed in detail. We emphasize the strong effect of meteor speed on detected Na/Mg ratio and argue that most previously identified Na enhanced with low velocities do not reflect atypical composition. According to our data, most of these meteoroids are probably of cometary or chondritic composition. Specifically, our results suggest that Na rich meteoroids are formed as fragments of Apollo type near-Earth asteroids.

- Several minor meteoroid streams were identified in our sample. For individual meteoroids, these results provide first spectral and physical data for meteors from smaller meteor showers. In future, these parameters could present first insights to properties of identified parent objects.

- Spectral and physical properties of Taurid meteoroids observed during the 2015 outburst were analyzed in detail. These meteoroids are thought to originate in the peculiar short-period comet 2P/Encke. Recently, numerous Apollo type asteroids moving within the Taurid complex were suggested to contribute to the activity of this shower [9, 13]. Large asteroidal debris within this stream could indicate the potential of dangerous impacts and meteorite production from Taurids. While our results confirmed the orbital similarities to the proposed associated asteroids, spectral and structural properties point towards heterogeneous cometary origin of majority detected meteoroids. The determined large variations of material strengths could imply the presence of carbonaceous inclusions within the cometary grains.

- We initiated a new project focused on linking the spectral classification of meteors from ground-based observations with high-resolution Echelle spectra of simulated ablation of known meteorites in high-enthalpy plasma wind tunnel. First laboratory experiment was performed at the Institute for Space Systems facility in Stuttgart [6]. Three meteorite samples of H-chondrite (Košice), L-chondrite (Northwest Africa 869) and achondrite (aubrite Al Haggounia 001) were tested. The preliminary results suggest that the proposed methodology can help to recognize meteoroid composition from specific spectral signatures. We aim to provide restrictions on the Fe/Mg ratio studied within the spectral classification to distinguish different types of stony chondritic material. The ablation process of one of the samples is displayed on Fig. 6.

Figure 6: The ablation of the L chondrite Northwest Africa 869 at the probe of the plasma wind tunnel of IRS.

Summary and conclusions

In this work, we demonstrated the capabilities of using spectral and network meteor observations of the AMOS system to study physical properties of meteoroids and indirectly probe the properties of their parent objects. The developed pipeline for processing, reduction and fitting of meteor spectra is suitable for studies of compositional variations among meteoroids and in combination with orbital and structural data can reveal the nature and origin of small interplanetary bodies. In future, the pipeline will be implemented with detailed fitting procedure based on physical model of meteor radiation, enabling the determination of relative elemental abundances from higher-resolution spectra.

We presented the first wide survey of spectral and physical properties of mm - m sized meteoroids. The obtained results reveal the compositional differences between cm-m sized and mm-sized meteoroids. The preservation of volatiles in larger meteoroids is directly observed. We have found overall increase of Na/Mg ratio compared to the population of mm-sized meteoroids. This distinction is caused by the weaker effects of space weathering (solar radiation, solar wind and cosmic rays), which less efficiently alter the bulk composition of larger meteoroids. We have detected very low abundance of iron meteoroids in our sample. This is in strong contrast to mm-sized bodies, among which irons dominate the meteoroids on asteroidal orbits. Our results suggest that most cm-m sized meteoroids on asteroidal orbits are chondritic. Moreover, new spectral group was discovered - Fe rich meteors, which show higher intensity of Fe compared to most chondritic meteoroids. We suggest that this group may contain iron enhanced (H-type) chondrites and bodies similar to stony-iron meteorites.

Thermal desorption during close perihelion approaches was confirmed as the main cause of Na depletion in meteoroids. Our results demonstrate that the alteration of meteoroids and loss of volatiles during this process causes hardening of meteoroid structure. Furthermore, the groups of Na enhanced and Na rich meteoroids are for the first time analyzed in detail. The strong influence of meteor speed (temperature) on the detected Na/Mg ratio for slow meteors is described. We suggest that part of Na enhanced and all Na rich meteoroids are of chontridic composition. While Na enhanced bodies are quite heterogeneous and also include cometary fragments, Na rich meteoroids represent fragments of Apollo-type near-Earth asteroids. Still, compositional Na enhancement was detected in two cometary meteors of Perseids and 49 Andromedids. We emphasize that the detected Na enhancement in majority of Na enhanced and Na rich meteors with low meteor speeds observed in this work and by other authors is influenced by the low excitation and probably does not reflect real compositional signature. The effect of Na rich spectra observed in very slow meteors was independently observed in laboratory experiment focused on simulated ablation of meteorite samples in plasma wind tunnel. We observed high-resolution Na rich spectra of meteorites ablating at conditions relative to the lower limit meteor speeds (10 km s^{-1} at 80 km altitude).

Several meteoroid streams were observed within our sample, enabling indirect probes into properties of their parent objects. Specifically, the spectral and structural properties of Taurids observed during the 2015 outburst were analyzed in detail. We confirmed the orbital similarities to the proposed associated Taurid complex asteroids. However, the detected spectral and material strengths suggest that these metoroids are of cometary nature with possible carbonaceous inclusions. We report on large heterogeneity of these bodies, including wide range of iron content and material strengths. These results imply inhomogeneous composition of comet 2P/Encke and possible presence of carbonaceous bodies within the Taurid stream.

Significant heterogeneity was also detected among several other meteoroid streams. We have have found that Perseids originating in comet 109P/Swift-Tuttle contain wide range of materials from Na poor to Na enhanced meteoroids. Significant structural and spectral differences were also found among the ecliptical α-Capricornids of comet 169P/NEAT and sungrazing δ-Aquarids of comet 96P/Machholz. The detected heterogeneities are affected by environmental factors and thermal history, but might also reflect real inhomogeneities of comet interiors. The heterogeneity of materials originating in one parent object can be also significant for asteroidal bodies, as was previously revealed from the Příbram and Neuschwanstein meteorite pair [12]. In case of sungrazing meteoroids, the dynamic age of these bodies is presented by the degree of Na depletion in their spectra. For the α-Capricornids, diverse light curves and emission spectra reflect structurally heterogeneous stream with high volatile content. We also presented first spectral data for individual meteors originating in several minor meteoroid streams.

Finally, we introduced newly initiated project focused on linking the spectral classification of meteors with high-resolution Echelle spectra of known meteorite samples during ablation. The simulated ablation is performed in a high-enthalpy plasma wind tunnel facility. The experiment aims to improve our abilities to recognize meteoroid composition from meteor observations. During the activity, we will focus on using physical model of meteor spectra to determine relative abundances of main elements and confront the results with real composition of ablating meteorite samples.

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2 publications in reviewed domestic journals

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