Description of the main research directions investigated by the Institute

The scientific life of the Institute is organized within four Departments. These are equivalent to Teams for purposes of the present Evaluation:

Department of Solar Physics (Team #1, head Mgr. Miroslav Bárta, Ph.D.) focuses on processes both in active and quiet solar atmosphere. Active processes affect the entire outer space including the Earth and its immediate environment (i.e., the space weather). At the Ondřejov Observatory, a long-term systematic study is carried out of the Sun in optical and radio wavelengths of electromagnetic radiation, and these observations are supplemented with the data gained thanks to the international cooperation from satellites providing information on solar radiation in the ultraviolet, X-ray and gamma-ray bands of the spectrum. Solar flares and prominences, structure and dynamics of the solar atmosphere and heliosphere, and space weather are examined. Processes in solar flares and prominences are numerically modelled with the particular emphasis on magnetic reconnection and the particle acceleration mechanisms. Regions of the Sun at different altitudes are studied in order to understand the interaction between the motion of plasma and the magnetic field. The dynamic phenomena of the solar wind are monitored, especially the formation and propagation of coronal mass ejections and their associated magnetic clouds, as well as the interaction of the solar wind with the solar system objects.

Department of Stellar Physics (Team #2, head Mgr. Brankica Kubátová, Ph.D.) studies the stars, especially the stellar winds and outflows, double and multiple stars, with the emphasis to their evolution, interaction and mass exchange in close systems. The research mainly concerns the class of hot stars (especially the spectral class B). These are highly luminous bodies, often showing the presence of a circumstellar disc of accreted material. The formation and physical characteristics of accretion discs are not yet satisfactorily explained. Their research is divided into a practical study of stellar spectra and a theoretical investigation of the atmospheres and stellar winds using the sophisticated numerical simulations. The studied spectra are acquired by the two-meter telescope in Ondřejov and at other observatories thanks to the international cooperation (mainly in the framework of our membership in the European Southern Observatory – ESO, and elsewhere within the collaboration). The Department also deals with the study of the white dwarfs, their classification and determination of basic physical parameters of the acquired spectra. More recently a new working group on exoplanetary research has been established. There is also ongoing research of galactic and extragalactic cosmic sources of high-energy radiation in visible light and in the field of high-energy radiation, namely, flashes of gamma radiation and their optical afterglows.

Department of the Interplanetary Matter (Team #3, head RNDr. Pavel Spurný, CSc.) conducts research of the small objects of the solar system, namely, meteoroids and asteroids. The department studies the interaction of the interplanetary objects of various sizes with the Earth's atmosphere, observes meteors and works on a theoretical interpretation of observations. The Team contributes and employs the European Fireball Network, which was founded by the Astronomical Institute and it continues to be organized by the Team. It also cooperates in similar activities connected with bolides observation worldwide. All of these activities generate highly visible results – the so-called Meteorites with genealogy. The observed data are used for the study of the physical processes during meteoroid penetration into the Earth's atmosphere, which includes radiation, ionization, and fragmentation. The physical characteristics and chemical composition of various types of meteoroids are determined, as well as their origin and distribution in the solar system, their relationship to comets, asteroids and meteorites. Furthermore, we study non-gravitational processes in small asteroids, binary systems and paired asteroids, and asteroids in excited (non-principal) rotation states. We also observe so-called Near-Earth Asteroids and their source regions.

Department of Galaxies and Planetary Systems (Team #4, head Mgr. Richard Wűnsch, Ph.D.) studies the evolution of isolated galaxies, galaxies in groups and clusters, the formation of stars and stellar systems. The Team explores the dynamics of the Milky Way galactic system – Magellanic Cloud, also free gas blown from galaxies due to their movement in the environment and spatially resolved spectroscopy of galactic nuclei. Observations in radio, infrared, ultraviolet, and X-ray bands are compared with the results of analytical models and computer simulations of gravitational and magnetohydrodynamic processes. The Team scientists are devoted to physics of compact objects (neutron stars and black holes) and study processes taking place in their vicinity. On the theory side, within the framework of the General Theory of Relativity the characteristics of the compact objects are analyzed and modelled, in particular, the nuclei of the active galaxies, neutron stars and microquasars. Modelling of multiwavelength characteristics of the produced electromagnetic signal is performed for spectra, polarization and temporal variability. Furthermore, as another research line, a part of the Team studies the rotation of the Earth, the orientation of its axis in space and the gravitational field.

Research activity and characterisation of the main scientific results

The research activities of the Department can be – by their nature – grouped into three main clusters: (i) Basic research of the physical processes at the Sun and in the Heliosphere, (ii) Research with more direct impact to applications, and, (iii) Observations & development activities in the scientific instrumentation, including services for the large international projects and infrastructures.

Basic research in solar & heliospheric physics

In line with the central mission of the Astronomical Institute, this type of activity is clearly the dominant one. In the period of 2014-19, the staff of the Department made remarkable headway in researching many particular open questions in solar & heliospheric physics. The most relevant results are briefly summarized in the bibliographic part of this report, here we try to describe the main landmarks in more detail and insert them into a broader context.

True 3D nature of the solar eruptions: Slipping magnetic reconnection revealed in modern observations. Magnetic reconnection is a key process for energy release in flares (and likely also for many other "explosive" phenomena at the Sun and in the Universe in general). Not only its energetic aspects are important in the solar context, but its role in restructuring the topology of the magnetic field as well. For example, it is essential for the ultimate release of the erupting filaments, which finally propagate as CMEs or magnetic clouds though the entire heliosphere, from the Sun. Many numerical models of the large-scale magnetic reconnection – until recently – stayed with the 2D (or 2.5D – including all three components of vector quantities) geometries. This approach, is actually, not so bad as the flare geometry usually has "an invariant" direction along the polarity-inversion line (PIL) and for the price of ignoring the "edge effects" and structuring along the PIL it provides much better computational resolution. However, we live in the 3D nature and thus the 3D aspects – especially when handling the eruption as a whole – are absolutely essential. The Paris-Meudon group (Aulanier et al., 2012) developed fully 3D model of eruption in the zero-plasma beta approximation. Many 3D-reconnection effects like the line slipping, predicted by earlier theoretical studies (e.g. Priest & Pontin, 2008), were shown essential in this flux-eruption model. The model also brought our deeper insight into the magnetic-topology change, between the erupting flux-rope, flare-loop arcades, and over-laying magnetic field lines. However, a question remained open, whether this *model* is really applicable for the solar eruptions and (eruptive) flares. In collaboration

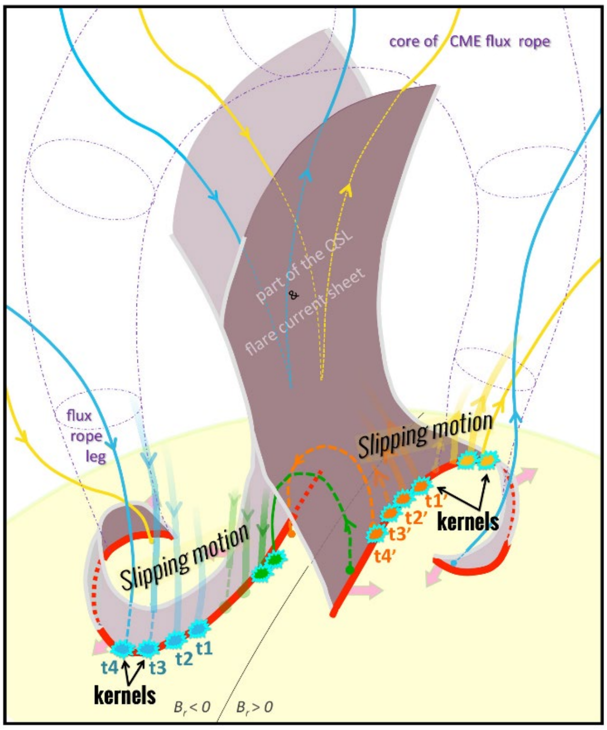

Fig. 1: Slipping of reconnected-line foot-points detected by moving kernels in Dudík et al., 2017.

with the French colleagues, the group from our Department (Dudík et al., ApJ, 2017; Sobotka et al., A&A, 2016; Zemanová et al., ApJ, 2019) showed unambiguously - by a careful analysis of data – the presence of the model-predicted features (line slipping traced by the bright-points motions in the flare ribbons, expansion/contraction of loops at the flux-rope flanks, dynamics of the 'J'-shaped ribbon hooks, etc.) in the real high-resolution observations of eruptive flares. The observational evidences for the 3D slipping reconnection model found by our analysis range from the signatures seen in the chromosphere by GREGOR up to the hot-corona EUV lines observed by SDO/AIA. The amazing agreement found between the model and in-depth analyzed observational data is important as it confirms that we are on the way to understand the physics of solar eruptions.

Fragmented reconnection in solar flares: Multi-scale aspects of the particle acceleration. In addition to the 3D nature of magnetic reconnection in solar eruptions and flares, its multi-scale character is important, too. In our previous studies (Bárta et al., 2011, Karlický & Bárta, 2011, etc.) we researched the spontaneous cascading fragmentation of the current layer in the solar flare into plasmoids, interleaved by smaller-scale current sheets. Resulting "fractal current sheet" (anticipated by Shibata & Tanuma, 2001) has consequences for so called fragmented energy release and particle acceleration. In collaboration with MPS Göttingen (Zhou et al., ApJ 2015, 2016) we researched particle acceleration in such a fragmented current layer (the result of our multi-scale high-resolution MHD simulations) for the first time, using the Test-Particle (TP) approach. The effects of particle drifts (curvature, gradient) in the turbulent magnetic field, and the resistive acceleration in multiple small-scale dissipation regions, were studied separately in two consecutive papers. It was found that the Fermi-like drift acceleration in the rapidly varying magnetic fields of the fragmented CS has a bigger impact to the total energy gain for a bulk of the TP electrons, however, the (rare) particles with the highest velocities gained their energies in the DC acceleration in the multiple dissipative regions. Our Team contributed with the high-resolution MHD model results that were used as an underlying field for the TP simulations. The result is essential for understanding how the particles are accelerated in flares. Namely, the fragmented nature of the flare current sheet can be – exactly through the particle acceleration processes – imprinted to the radio data received by our sensitive and high-cadence radio spectrographs (*Observing infrastructures* below) and compared with the model.

Accelerated particles in flares: Mystery of energy deposition scenarios. Fraction of the particles accelerated in the current layer in the solar corona propagates downward, towards the Sun, reaching finally the denser layers for the solar atmosphere. Here, their energy is deposited and eventually thermalised. The question, however, persists, how this process actually runs, what are, e.g., the heights of the energy deposition and, consequently, what are the radiation signatures of those processes in the observed spectrum. The process is very complex with mutual bi-directional dependencies between population of the accelerated particles at a given height, temperature and density structure (including, e.g., generated shock waves) in the location of the energy deposit, and the radiation field. Using the combined approach of radiative-hydrodynamics (RHD), including the non-LTE radiative transfer, and particle-energy deposition calculations carried out in the FLARIX code, the (bit unexpected) height distribution of the energy deposition was found, together with its consequent radiation manifestation in the form of visible-continuum enhancement. This enhancement in the higher layers was confirmed by the off-limb observation of the solar flare (Heinzel et al., ApJ, 2017). After the continuum enhancement was revealed in the UV (Heinzel and Kleint, 2014) and later also in the optical and IR radiation (Kleint et al., ApJ, 2016), this result represents a solid explanation based on the advanced combined physical modelling. The significance of the result exceeds the field of solar physics and it is relevant for manifestation of flaring activity at stars, too. A possible connection between solar and stellar flares on the ground of similarity in continuum enhancements also started to be studied observationally by our Team (see *Observing infrastructures* below). Till now the stellar flares have been characterized mostly by their light curves, but, in fact, explosive phenomena with quite different underlying physics may exhibit similar radiation-flux dynamics. On the other hand, the enhancement in particular spectral domains can help to distinguish between the flare-type and a different activity going on the star.

Non-Maxwellian solar plasma and its signatures in the emitted spectrum. As it was mentioned in the paragraph above, the transport of energetic particles from corona to the denser layers, where they are eventually thermalised, is a complex process and for quite some time the particle velocity distribution function is far from the Maxwellian equilibrium. Moreover, (frequent) presence of turbulence and waves results in the secondary, local, energisation of particles. There are other statistics, which can describe the energy distribution function in this non-equilibrium state better – both on theoretical grounds (e.g., Tsallis entropy generalisation for non-equilibrium systems) and because of better agreement with observations. One of them is so called kappa-distribution. The radiation calculations based on the assumption of non-Maxwellian plasmas fit the observed spectral features better, yet with a smaller number of free parameters (density+two parameters of kappa-distribution vs. multiple two-parametric gaussians in the multi-thermal description). The group at our department made a big progress in studying the kappa-distribution present in the solar atmosphere not only in such a non-equilibrium-situations like solar flares, but also during say, “standard” processes leading to the quasi-continuous heating of the solar corona. Above all, the freely available software package & database *KAPPA* was developed at the department (Dzifčáková et al., ApJSS, 2015). The SW enables calculations of optically thin spectral lines for non-equilibrium distributions, namely the kappa-type, and this way it represents a generalization of the well-known package CHIANTI, where similar calculations are provided for the Maxwellian equilibrium plasmas. Using the KAPPA package and comparing the modeled spectra produced by this tool with the observed ones, the presence and parameters of the kappa distribution was found in a variety of situations in the solar atmosphere – flares, transient coronal loops, transition region (Dudík et al. ApJ, 2017, Sol. Phys, 2017; Dzifčáková et al. ApJ, 2018). Hence, the results of this group have shown the omnipresence of the non-Maxwellian plasmas in the solar atmosphere, surprisingly even under the “quiet” conditions.

Radiative transfer – a key to decipher the information in spectroscopic & spectro-polarimetric measurements. While the above described research is focused on departures from the thermodynamic equilibrium of plasmas, similar effects are important for the radiation field, too. The significance of the so-called non-LTE approach for a correct interpretation of continuum enhancements in the flaring solar atmosphere under bombardment of energized particles has been already mentioned above. But there are many other situations, where the radiation is not in local equilibrium with the medium it propagates through and this effect strongly influences the shape of spectrum of the outgoing radiation, which we finally receive by our instruments. And vice versa – should we be able to decipher the information contained in the (multi-wavelength) spectroscopic measurements and reveal the structure of the medium, in which the radiation is formed (and/or through which it is transmitted) via spectroscopic and spectro-polarimetric (SP) inversions, the (Stokes) spectrum formation calculations frequently need to involve also the non-LTE physics. This issue represents a long-term research topic within our team. In the recent period we have achieved significant headway namely in the three following directions of this research: (i) Full 3D Non-LTE radiative transfer (RT) of the polarized light (full Stokes vector), (ii) Extension of our non-LTE models/codes to new spectral lines available from the modern spacecrafts, and (iii) Applications of spectro-polarimetric inversions (both LTE and non-LTE) to modern high-resolution data – from both ground-based and space-born instruments. In the following we present a few illustrative result examples for all three sub-topics:

Probing structure of the chromosphere and transition region by magnetically-sensitive spectral lines. Modern spectro-polarimeters allow us to probe density, velocity, temperature, and – via the Zeeman and Hanle effects on the polarized light – also the magnetic structure of the solar atmosphere. As it has been already written, in order to make use of the spectro-polarimetric information for revealing the 3D maps of plasma parameters, the influence of the distribution and gradients of those parameters onto the (Stokes) spectrum formation under general non-LTE conditions must be understood. Our team members significantly contributed to this knowledge by the 3D non-LTE Stokes RT code *PORTA* and its application to the (i) MHD-modelled solar atmosphere (chromosphere + transition region) for magnetically sensitive Lyman-α line (Štěpán et al., ApJ, 2015), and, (ii) An easily controlled 'toy-model' of the structure of the solar atmosphere, which enabled to study the influence of gradients of temperature or velocity field to the polarization signal in the chromospheric Ca II (8542 Å) line. The first result has a direct application for comparison of the MHD model with the measurements of the CLASP (Lyman-α spectro-polarimeter onboard a rocket) instrument, the latter contribution shows that the inhomogeneities in plasma structure may effectively mask the influence of the magnetic field on the polarized-light signal. This has general relevance for the SP methodology.

Solar plasma diagnostics using Mg II lines observed from space. As an example of the recent development in our RT expert group targeted at the extension of the non-LTE radiative transfer and spectrum formation calculations to new spectral windows, an inclusion of spectral lines invisible from Earth into our codes can be adduced. The importance of this upgrade is clear, if we take account of that many space-born devices oriented at high-dispersion solar spectroscopy were launched during (or shortly before) the period (e.g. IRIS, SDO/AIA) and their new high-quality data call for interpretation. The newly extended non-LTE RT code was applied for Mg II line observed from the IRIS instrument. First (Liu et al., Sol. Phys., 2015), the X-class flare was studied using the IRIS slit-scanning mode and by means of fitting the non-LTE calculated Mg II profiles (strongly enhanced by the flare) in bright kernels in the flare ribbons with the observations, the structure of the solar atmosphere and its dynamics in those kernels were revealed. The position, structure and time evolution of the Mg II kernels were also compared with the hard X-ray emission brightenings – this is again important for the research of the yet open question of the flare particle-beams energy deposition. Another application of the extended non-LTE spectrum formation code aimed at the cool flare loops, again observed by IRIS in the Mg II line (Mikula et al., ApJ, 2017). Such loops are expected (by models) to be present at other flaring stars, too, and the Mg II line analysis can represent a sensitive indicator for distinguishing the solar-like flares from the other sudden-brightening events at the star. The non-LTE inversion of the line revealed plasma in a highly dynamical state even in those cool loops.

High-resolution SP inversions and the white-light flares. For the sake of illustration of the third aspect of the continuing development in our RT calculations and line inversions – their applications to the newly emerging issues induced by modern, high-resolution data – a couple of examples are presented. As the first one, let us adduce a new light that the high-resolution SP inversions shed on the above discussed issue of the energy deposition, heating, and continuum-emission enhancement in the flaring solar atmosphere. Namely, the polarization signal reveals the magnetic structure of the observed region, which provides very important context information, e.g., for possible trajectories of the bombarding particle beams, propagation of shocks, etc. Our Team studied an example of the white-light flare with the so-far unprecedentedly high spatial and spectro-polarimetric resolution (Jurčák et al., A&A, 2018) and used the SP inversions to the detailed investigation of heating of the flaring solar atmosphere structured by the magnetic field.

Estimation of the chromospheric heating by acoustic waves. Another example, where the SP inversions with high time cadence revealed the structure of the 'quiet' solar atmosphere and its wave-dominated dynamics, is the study of chromospheric heating by propagating acoustic waves (Sobotka et al., ApJ, 2016). Having the quite complete information on the atmospheric structure at different height levels, including its time evolution, the authors were able to calculate the wave-energy flux and its decrease with the height ascribed to its thermalisation. The high-resolution (in all spatial, temporal and SP domains) allowed for the first really qualified estimation of share of the waves to the heating of the upper chromosphere and shed a light to the long-term debate on the solar atmosphere heating.

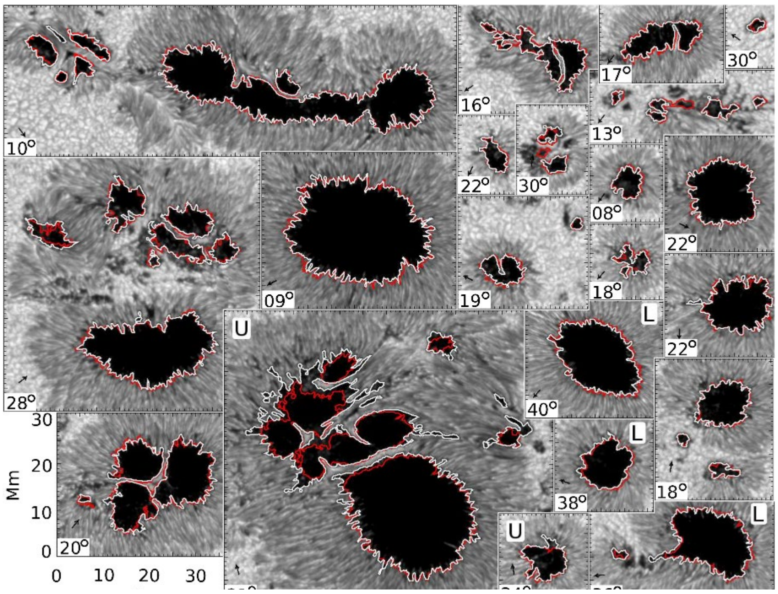

Fig. 2: Jurčák's criterion – the umbra/penumbra boundary (white contour) corresponds quite universally to the level B_{ver}=1850 Gauss (red contour). Only unsteady, still developing magnetic elements show differences. Jurčák et al, 2018.

Umbra/penumbra border line in sunspots: Do we see a sharp transition between two magneto-convection regimes? The sharp border line (a sudden drop of intensity) between umbra and penumbra visible in the white-light images of the sunspots is remarkable. There were several attempts to relate the position of this boundary to the magnetic field properties – e.g., to its magnitude or inclination. In the paper by Jurčák et al. (A&A, 2015) it was convincingly shown, that after a transition period of time, during which the penumbra is formed, the emission-intensity drop line corresponds quite exactly to the boundary between the regions, where the strength of the vertical component of the magnetic field is higher than a critical value ~1.8 kGauss (umbra), and where it is less. The critical value for B_{ver} is quite a universal constant for all sunspots and this division between umbra and penumbra based on B_{ver} value is nowadays frequently referred as *Jurcak's criterion* in the literature. Its validity was later extended to the smaller magnetic elements, too (Jurčák et al., A&A, 2017) – it was shown that pores, whose vertical component does not reach the critical value, are unstable and are consecutively "consumed" by the evolving penumbra. On the other hand, the pores, which have (an internal) region where the B_{ver} is super-critical, evolve eventually into the "standard" sunspot with umbra and penumbra. This universal empirical rule seems to have a deep physical background: Modern MHD simulations of the sunspots show that the critical value of the vertical component of magnetic field separates two distinct regimes of magneto-convection. This way our result contributed significantly to understanding physics of the sunspots and pores and related the notoriously known but until now a bit mysterious border line between umbra and penumbra to the deeper underlying physics. The work on relation between MHD simulations and high-resolution observations of the sunspots continued by a study of the relation between magnetic field and temperature in the sunspot penumbrae – such a comparison of the model prediction with the data obtained by SP inversions (Sobotka & Rezaei, Sol. Phys., 2017), was also done for the first time.

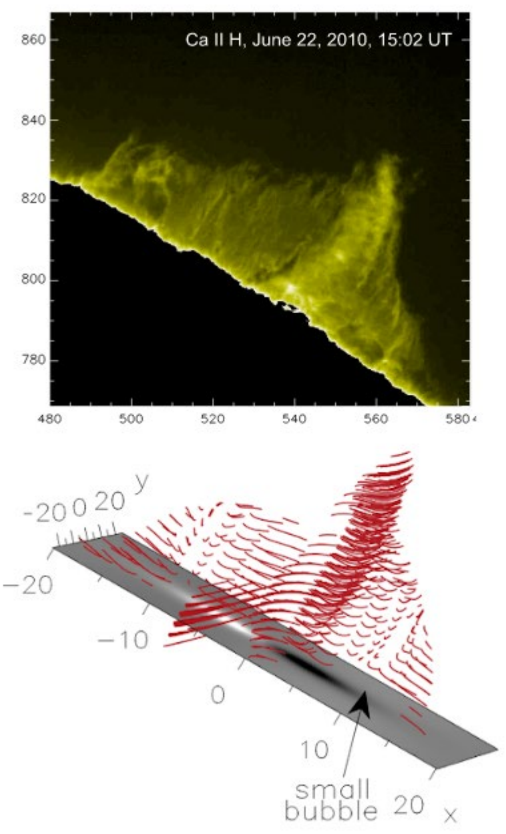

Fig. 3: Observed fine structure of solar prominence compared with the WPFS model. Gunár et al., 2018

Fine structure of prominences: Non-LTE calculations and predictions for ALMA observations. Both the modern high-resolution images on one side, and difficulties with fitting the observed spectra of prominences to their older compact models on the other side, led to the change of paradigm in the recent past years and a new picture of the prominence as a cloud of thinner threads of the cool material deposited in many local magnetic dips emerged. The prominence modelling and non-LTE calculations of the prominence spectral line formation belong to the traditional research topics in our department. Its recent development takes advantage of the opportunity, which is offered by the modern multi-threaded prominence models based on searching of the magnetic dips in the non-linear extrapolations of the photospheric magnetic fields to the upper atmosphere. In an international collaboration with the University of St. Andrews (providing the NLFF extrapolated magnetic field) a new 3D *Whole-Prominence Fine Structure* (WPFS) model was developed, based on the filling the extrapolated magnetic structure by plasma in (magneto-)hydrostatic equilibrium (Gunár & Mackay, A&A, 2016). The temperature and density prominence structures in the WPFS model correspond well to those inferred by the non-LTE "inversions" of really observed prominences.

It was shown that – consistently with the model assumptions – the plasma beta is low enough almost everywhere, with exception of the densest parts of the threads. Our modelling continued by extension of the 3D density & temperature map in the prominence to its expected (ideal) sky-brightness maps as it could be seen in the millimeter wavelength domain continuum (Gunár et al., ApJ, 2016). The result was very important in view of starting solar observations with ALMA (Spring 2017), and the predictions made by the model were later actually confirmed by ALMA prominence observations. Since our Team is deeply involved in the *Solar ALMA ObsMode* development and has been participating (as the European ARC leader) in the Commissioning and Science Verification of solar observations with ALMA (see details below in the ALMA-specific section), the result was also used as a reference use-case for prominences in the Development Study Report: Solar Research with ALMA delivered to ESO. Because of immediate application of the result for coming ALMA observations, we extended our study of prominence appearance in ALMA images by atmospheric and instrumental effects at the ALMA observing site. To that end, we used H-α image of the prominence with a medium resolution (~1") comparable with the expected ALMA Band 3 images in compact array configurations, re-calculated it into (ideal) brightness map at 3 mm using the relation between H-α total intensity and brightness temperature (derived by Heinzel & Jejcic, 2009), and calculated the simulated interferometric visibilities of that map, degraded by the instrumental and (Earth) atmospheric effects. The simulated visibilites were finally processed (IFT+clean) in the standard SW package CASA in order to get the prominence maps as ALMA would see it. The results demonstrated the role of specific parameter settings in the CLEAN procedure, namely the importance of the multi-frequency (MFS) synthesis for the solar images. The result has a significant impact on the world-wide adopted procedures for the solar ALMA data processing.

Oscillations and (quasi-)periodic processes in the solar atmosphere. Oscillations and waves are omnipresent in the entire solar atmosphere. Since their (quasi)periods depend on the parameters of the medium in which they propagate, their analysis has quite a big diagnostic potential. In analogy with similar usage of the waves generated during the earthquakes and propagating through the body of the Earth, we speak about *helioseismology* (propagation in the photosphere and sub-photospherical layers) or *coronal* (loop) *seismology* (probing structures in the solar corona). These modern methods are being developed and applied to selected research problems also in our Department in the last couple of years. A few examples of the recent results follow right now.

Helioseismologic inversions for investigation of the large-scale flow structure at the Sun. Our Team members uses the time-distance (local) helioseismology method for investigation of the large-scale flows in and under the solar photosphere. Namely, the super-granular flows are one of the long-term research topics of one of ours WGs. Earlier they were studied by a more traditional method, like feature tracking, nowadays the research is extended by the usage of the modern ones, right that based on the local helioseismology. Nevertheless, as the results reached in this field showed (Švanda, A&A, 2015), the method based on the time-distance helioseismologic inversions are far from providing unique solutions, i.e., the flow structures: Many different flow structures can result in the same measured signal. The result is of much more general relevance – it shows the possible weak points of the method and warns of its blind usage. In an international collaboration the method was also used for studying the flows at even larger scale: Meridional circulation and differential rotation of the Sun as a whole. In order to validate the recent helioseismologic methods, their results were compared with those obtained by more traditional feature (Coherent Structures) tracking (Roudier et. al., A&A, 2018). It was shown that within the uncertainties the result of both methods is the same. This cross-validation is an important outcome because the new method can also study weak variations of the flows on a much shorter timescale.

Flare-generated pulsations as a unique diagnostic tool for physics inside. Many types of (quasi-) periodic oscillations are detected in solar coronal loops, in particular being driven by the dynamic processes running in the solar eruptions and flares. One of such process is the cascading fragmentation of the flare current sheet (CS) inherently connected with formation of plasmoids and their subsequent motions and mutual interactions. Since the plasmoids sizes in the flare current sheet occupy (as expected by the model, e.g., Bárta et al., 2011) all range of dimensions from a few tens of the dissipation scale up to a few thousands of kilometers, also their dynamic times vary from very sub-second scales (oscillations during merging of small-scale plasmoids) up to minutes (travel time of large-scale plasmoid along the flare CS). In order to investigate the dynamics of plasmoids as possible drivers of observed pulsations, we studied an interaction of the large-scale plasmoid with the flare-loop arcade (Jelínek et al., ApJ, 2017) using MHD numerical model. It was found that “a fall” of plasmoid to the arcade loop-top leads to several periods of system oscillations, until the plasmoid merges into the loop system. Such oscillations could have observable signatures in, e.g., the position of the loop-top HXR source and the modulation of its signal, or in the dynamics of the separation of the flare ribbons.

Plasmoids of smaller sizes, closer to the dissipation scale, and their mutual coalescence have a direct connection to the rate of magnetic energy converted in the reconnection and thus to the injection of accelerated particles into the flare volume. Such injected beams can be detected by quite sensitive radio spectrum measurements. And exactly such expected quasi-periodic broad-band radio pulsations at the sub-second timescale were observed with our instruments in the GHz frequency range. We studied this radio-detected signatures of small-scale fragmented energy release in the broader context of multi-wavelength observations – multiple plasma (presumably reconnection) jets were also found in the EUV data (Meszárosová et al., A&A, 2016). The result supports the fragmented ‘multi-site reconnection’ paradigm for solar flares.

The (quasi-)periodic modulation of the injection of accelerated particle beams represents one possible source of the observed pulsations. Others are the already above-mentioned oscillation eigenmodes of the loops or interacting arcade/plasmoid system. Nevertheless, other possibilities need to be investigated. To that end, we (Karlický & Jelínek, A&A, 2016) simulated (and estimated the possible outcome in form of detectable pulsations) a process, where thermal shock – generated by an impulsive bombardment of the dense layers by energetic particles – propagates along the flare loop with several reflections at the photosphere (thermal shock bouncing). The result shows that this process can explain so far mysterious time-scales of pulsations observed in some flares. Because of the expertise of our group in the topic of oscillations of magnetic structures in the solar corona, we were invited to the international collaborative paper that broadly reviews this general plasma-physics phenomenon across many environments (corona, heliosphere, planetary magnetospheres; Nakariakov et al., Space Science Reviews, 2016).

Oscillations and rotation-like periodic motions in solar prominences. Solar prominences also exhibit periodic type of motions. Mostly they are detected by measuring the Doppler velocities in prominence spectra (also with our instrumentation – see below). However, some weak quasi-periodic motions observed this way may represent a false detection and are in fact induced by the (Earth) atmospheric turbulence effects in the air mass above the telescope. In order to estimate the fraction of false-detected periods, we performed two-site simultaneous observations of the prominence oscillations in collaboration with University of Wroclaw (Zapiór et al., Sol. Phys., 2016). Mutual distance of the two telescopes (feeding the spectrographs) cancels the atmospheric effects and it was shown that actually only few detected periods are inherently related to the prominence dynamics. The results have a more general impact as a warning against searching blindly the (quasi-)periods in the single-telescope data without estimating the influence of atmospheric and instrumental defects to the observed data. A careful analysis of prominence observations revealed another type of "optical illusion" – appearance of some prominences in the form of "tornadoes". In order to track a real 3D motion of identifiable plasma blobs in the prominence volume, we helped (in an international collaboration) to extend the 2D velocity information in the image plane by the third component of their velocities measured spectroscopically by the Doppler shifts. Assuming that the blobs are "falling" along the magnetic field lines, the 3D magnetic structure of the prominence was revealed. It was shown that the circular/helical motions of the blobs are quite frequently merely illusion (Schmieder et al., A&A, 2017), so the "tornado" is a misleading name in this context.

Kinetic-scale plasma processes at the Sun seen in high-resolution radio spectra. Diagnostically significant solar radio emission (i.e., the radio bursts) at metric and decimetric wavelength range is inherently connected with the kinetic-scale plasma processes like instabilities of non-Maxwellian particle distribution functions (beam-type, loss-cone, temperature-anisotropy, etc.). One of the many types of solar radio bursts, the spectacular "zebra pattern" (along with the Sun it is also observed in the magnetosphere of Jupiter or in the Crab nebula), can be used for quite an exact estimation of coronal density and magnetic field in its source. The proposed diagnostics is based on the widely accepted emission mechanism for the zebras – so called double-resonance instability of the upper-hybrid (UH) waves (Zheleznyakov & Zlotnik, 1975). This instability generates waves with frequencies in a series of harmonic resonances – then each one represents one zebra stripe in the spectrum. The open question remains, how to ascribe the harmonic number to the given observed stripe. This uncertainty has so far prevented the accurate usage of the zebra observations for inferring the plasma parameters inside the source. Using analytical calculations and Particle-In-Cell (PIC) plasma simulations of the UH instability, the method for this identification was presented for the first time (Karlický & Yasnov, A&A, 2016).

In another paper (Karlický, ApJ, 2015) we studied confinement of the hot electrons by self-generated thermal front at the plasma kinetic scale. Using the PIC-simulation it was found that the thermal discontinuity suppresses significantly the electron flux from the hot to the cold region. At the same moment, the thermal front moves and this process can manifest itself by a characteristic signature in the radio spectra. An example of such signature found in our radio data was presented. The result also shed light on the so far mysterious long-duration HXR sources, whose hot-electron contents had been supposed to dissolve much faster.

Kinetic-scale plasma processes in the solar wind: Models and *in-situ* measurements. Thanks to the availability of the *in-situ* measurements (nowadays also by Solar Parker Probe and Solar Orbiter), the solar wind is a perfect laboratory of dilute, turbulent, magnetized plasmas and a test-bed for our theoretical and modelling approaches to such environment, which have much broader relevance in plasma physics and its applications (e.g. in controlled fusion). In this field, our group contributed namely by (i) Analytical calculation of the generalized plasma dispersion tensor under presence of specific distribution functions, and (ii) Hybrid simulations of plasma instabilities and turbulence in the solar wind. The first result (Vandas & Hellinger, Phys. of Plasmas, 2015) represents a significant extension of analytical dispersion-tensor calculations done so far for simpler particle distribution functions by the ring-type particle distribution, frequently found in the solar wind. The result is important for analytical calculations of possible plasma instabilities that may result from the presence of ring-type distributions in plasmas.

The latter contribution – thanks to the “mezzo-scale” applicability of the hybrid simulations – provided a bridge between various concepts of plasma descriptions and this way enabled their cross-validation. As an illustration of this fruitful approach, the verification of the specific Hall-MHD approximation to the turbulence based on a new form of the von Karman-Howarth equation using concurrent description by the fluid and hybrid approximations in their common domain, can be adduced (Hellinger et al., ApJL, 2018). The newly verified von Karman-Howarth fluid approximation can be now used on a more extended range of scales with much fewer computing resources than fully kinetic or hybrid approaches. In another paper, the hybrid code was used for the extension of the plasma-kinetic analytical description of the fire-hose instability in the solar wind to its non-linear regime (Matteini et al., ApJ, 2015). And as a final example of such a useful bridging across the scales, let us adduce the hybrid simulation of the mirror instability running on the background of the developed multi-scale turbulence in the solar wind (Hellinger et al., ApJ, 2017). The simulation found that the mirror instability is not suppressed by turbulence and its structures can coexists on top of it. Since the process contains both ion-kinetic and hydrodynamic scales (it spans from the ion skin depth to the turbulent-cascade energy input scale, taking account of the solar-wind expansion in the co-moving reference frame), only the specific hybrid approach used in the paper was able to treat all involved processes self-consistently. The result is important for understanding modern *in-situ* measurements of the solar wind parameters.

Closer to applications

Albeit the mass-center of the activities carried out at the Institute is by its foundation in the science and basic research, some results obtained in the field of solar physics, namely the influence of solar activity to the Earth and our civilization, are closer to applications. In the following text we briefly describe three illustrative examples reached during the last five years.

How frequent are the harmful solar eruptions? Solar eruptions and flares can have a significant and multi-channel impact on the Earth, namely on our modern sensitive technologies. The means of their influence range from a collision of the magnetized cloud/ejected CME with the Earth's magnetosphere, leading to geomagnetic storms and geomagnetically-induced currents (GICs), through the interaction of energetic particles and radiation with the upper atmosphere, up to enhanced radio noise interfering with our communication or navigation devices. As our civilization becomes more dependent on technologies, expected damages caused by a possible major solar event increase rapidly. Indeed, the famous Carrington event (1859) (among other remarkable effects) damaged a few telegraph lines (there were not so many such lines those times) but if an event of such magnitude appeared nowadays, they say that our civilization would be practically switched off for more than three months and the damages would hardly be enumerated in money. Naturally, a question arises, how frequent are the major events like that in 1859. Since historical written records are quite short in order to make a statistic solely from solar events, a plausible way out is to increase the statistical ensemble by taking account of many Sun-like stars. These so called 'solar-stellar connection' studies appeared in the last decade. Their number increases because of (i) the practical motivation mentioned in this paragraph, and (ii) the means of detection of flares at the other stars increased in the past few years thanks to the space missions oriented namely to the popular research of exoplanets.

Our group does not stay behind the development and we published (mostly in international collaboration) a bunch of papers on this topic. In order to use the other stars as a part of the ensemble for statistical scaling of the magnitude of solar events, one has to carefully study the similarities and differences between the Sun and other stars. Švanda and Karlický (ApJ, 2016) studied the ensemble of flaring A-type stars recorded by the Kepler exoplanet mission. By methods of the statistical correlation between the flare energetic spectrum and (non-)presence of stellar coronae they studied the relation between coronae and flaring activity. They speculate that the flares at the stars, which have the hot coronae, contribute to their (corona) maintenance. In the following paper (Balona, Švanda & Karlický, MNRAS 2016) the authors studied a broader range of stars from A to M spectral type, again using the Kepler-mission archive. They found correlation between the flaring activity and the star rotation rate as well as between the presence of star-spots and the flares. These correlations strongly indicate that the flares at stars – defined phenomenologically as a sudden rise of light curves (in specific spectral channels) followed by slower decrease – are, in fact, of similar nature as the solar flares; that their common underlying physics is a sudden release of stored magnetic energy. In order to bring further evidence for qualitatively the same – just up-scaled in magnitude – background mechanism of stellar and solar flares, we study the enhancements in specific ranges of spectral continua as it has already been described above (Heinzel et al., ApJ 847, 2017). Such broad-band observational features are more robust and more likely to be detectable also at the (remote) stars, where we lack the spatial resolution. Specifically, there is a practical question, whether we can have – in principle – a super-flare at our Sun, i.e., whether the detected stellar superflares are just up-scaled solar-like flares. To that end we contributed to the discussion by a paper *Can Flare Loops Contribute to the White-light Emission of Stellar Superflares* (Heinzel & Shibata, ApJ 859, 2018). As it has already been claimed: The clarification of the similarities/differences between the phenomena of solar and stellar flares is essential for using the stellar data as an extension of solar flare statistics and, consequently, making a qualified estimation of major solar event probability of occurrence (magnitude vs. typical period of recurrence).

Can even the middle-magnitude events lead to cumulative damages in power grids? The large solar eruptions (when hitting the Earth) are undoubtedly harmful for our infrastructure namely to the power grids by action of the above mentioned GICs. But what about cumulative effect of the middle-magnitude events? This question was addressed by Výbošťková & Švanda (arXiv:1709.08485, in Czech), who statistically studied the failure rates in the main Czech power transmission system operated by the Czech national operator ČEPS vs. the space-weather effects. They showed that the effects of solar activity on the failure rate in the back-bone power grid cannot be excluded even for our central-European country (i.e. rather far from the geomagnetic pole). Namely, the middle-size geomagnetic events (substorms) may lead to unnoticed partial damage or performance worsening of the power-grid devices (e.g., transformers), which may then fail later, during the next overload. In this direction, M. Švanda had also made a study *Risks of solar flares for the nuclear power plants operated by the Czech Energetic Company (ČEZ),* on request by the Czech Energetic Company (2016).

Direct influence of solar radio bursts on GNSS systems. Solar flares and eruptions do not affect our technologies only by the best-known GICs, but via many other channels. One of them is also quite a known effect of highly dynamic variability of the total electron content (TEC) in the Earth ionosphere due to ionizing radiation (plus particles and atmospheric currents) enhancements during the flares. The TEC variability has a direct effect on the global navigation satellite systems (GNSS; specifically e.g. GPS, Galileo, GloNass, etc.) as it inserts hardly-predictable time delays for the radio (L-Band) signal travelling from the satellite to the navigation receiver. Much less it is known that even the solar *radio* emission can reach such high spectral flux density that it interferes the GNSS radio communication, and the satellite navigation is not just inaccurate (like in case of the TEC irregularities), but – in extreme cases – even completely impossible. One such case of a major flare was studied in an international cooperation (namely with DLR) and the results published as a paper *Solar Radio Burst Events on 6 September 2017 and Its Impact on GNSS Signal Frequencies* (Sato et al., Space Weather 17, 2019). Our group contributed by in Europe unique measurements of solar radio spectra of that event; the figure of our spectrum was selected for the front page of the SW journal issue. Our radio spectrographs (see below) operate exactly in the L-Band, where the GNSS communications run, too.

Solar activity forecasting. Last but not least in this direction, our Department operates the *Solar Patrol Service* (in more detail described below). This service – among other activities – works as a national reference for predictions of the solar activity and related space-weather effects. We provide these forecasts to the TV (presented daily on the Czech Television as a part of the weather forecast) and radio broadcasting, press agency, and for approximately 50 Czech and international users (radio communications, radio amateurs, ISES, SIDC, and others). At the same moment, the service is involved in the international networks (details below).

Observing (and computing) infrastructures

Our Team operates (and further develops) several in-house observing (and computing) facilities and in addition to that, it is involved in the development and operation/services for a couple of major international infrastructures and projects. Let us start with a brief description of the recent development in our local infrastructures.

Solar Patrol Service. Solar Patrol – as already mentioned – works as a national service for monitoring and forecasting of the solar activity & space weather. It works in a frame of the *International Space Environment Service* (ISES) and its *Regional Warning Center* (RWC) Prague. At the same moment it is involved in *Sunspot index and long-term Solar Observation* (SILSO) and *CV-Helios* international networks for monitoring and classification of the solar magnetic activity manifested by sunspots, and for the activity forecasting. The patrol operates three small full-disc refractors for drawings, white light, and Hα, and two 20-cm refractors for imaging of active regions in the photosphere and Hα chromosphere. An upgrade of cameras and steps towards a better automation of the telescope control were undertaken during the past few years. The time of low solar activity around the minimum was also used by our operator for digitization of the archive of our older paper records, not only from Ondřejov but also from a series of observing stations on the territory of the Czech Republic and Slovakia. The web interface for the forecasts and monitoring was rebuilt completely, too. In 2019 we started negotiations on a possible incorporation of our SPS into the *Solar Weather Expert Service Centre* (S-ESC) working in frame of the ESA's Space Situational Awareness (ESA SSA) programme oriented to the space weather; the negotiations are underway. At the end of 2019, our SPS also undertook steps towards inclusion into *Flare scoreboard* – NASA operated validation programme for solar flare forecasting. More details on instrumentation, activities, observation records etc., can be found at the SPS web site http://www.asu.cas.cz/~sunwatch.

Solar optical spectroscopy labs. The department currently operates two solar spectroscopic labs: (1) HSFA2 – the 0.5-m horizontal solar telescope equipped with a large multichannel slit spectrograph observing in five spectral regions simultaneously: Ca II H, Hβ, Na I D and He I D3, Hα, and Ca II 854.2 nm. The spectrograph is used for our research in solar flares and prominences; during the last years namely the observing programme targeted at the research of prominence 3D structure and oscillations ran (see the published results above). The device is also often utilized in coordinated campaigns with other European space and ground-based instruments. A major upgrade of cameras to higher resolution & cadence was carried out at the end of 2019. The details on the instrumentation and the data archives are available at http://www.asu.cas.cz/~sos/.

(2) In 2018, two low-dispersion spectrographs *Ocean HR4000* in near UV and visible channels were installed in the no more used laboratory of historical *Multi-channel Flare Spectrograph* (MFS; Valníček, Švetska et al., 1959). They are fed by the still operating original MFS telescope and heliostat. The goal of the research is to mimic observations of the Sun as a star – quite a significant part of the solar surface is selected around the active region and model-predicted (already mentioned by Heinzel et al., 2017) specific enhancement in continua is searched in the spatially-integrated signal from that area. Such a robust detection technique could be used for searching of this feature in the stellar flares, too.

Enhanced solar radio spectrographs – from RT5 to OSCARS. The group has (already for decades) been operating three radio instruments for solar research – radiometer RT3 @3GHz with time cadence of 1ms, and two radio spectrographs (RT4 and RT5), each composed of 256 frequency channels spanning over the ranges 0.8 – 2.0 GHz (RT5) and 2.0 – 5.0 GHz (RT4), fed by 10m (RT5) and 3m (RT4) parabolic dishes. The spectrographs are unique instruments in the European time zone and observed frequency range, and provide results used in many of our research publications (see *Basic research* above) as well as for direct application in the GNSS interference by the solar bursts (as mentioned in *Applications*). The data archive and the details on the instrumentation can be found at http://www.asu.cas.cz/~radio/. Motivated by our research interest in the multi-scale fragmented magnetic reconnection, whose model predicts radio-burst sub-structures at the short time scales, and also by the above mentioned new practical application of our measurements in the GNSS interference research, we decided to upgrade our channel-sweeping spectrograph RT5 with (practically usable) time resolution 10ms and the channel width of 4 MHz to a fully digitized FFT-based device. The new spectrograph (Ondřejov Solar hi-Cadence Automated Radio Spectrograph – OSCARS) was designed in collaboration with Faculty of Electrical Engineering TU Prague (details in Puričer, Kovář, & Bárta, Electronics 8, 2019) and its main advantage is that it provides higher spectral (1 MHz) and temporal (1ms) resolutions with yet better sensitivity and S/N ratio. The new spectrograph is currently (since September 2019) cross-tested with the existing older RT5 device and later it shall replace it. The similar upgrade is envisaged for the higher-frequency RT4 spectrograph, too.

HPC cluster OASA, solar data servers. Our numerical simulations and ALMA data processing demanded a new computer cluster OASA, basically replacing the old one (OCAS) built in 2005-2007. Although it represents an all-institute HPC infrastructure, used by all its departments, the major share on its building (project design, execution, and management) was done by the Dept. of Solar Physics. The cluster started serving our community in January 2017. We are also operating three larger servers for processing, archiving, and publishing (via web interface) our own data.

It is hard to omit our participation in big international infrastructures in this section completely – let us mention it at least briefly, the details are below in chapter *Participation in large collaborations.*

ALMA. Solar physics, together with the galactic & extragalactic astrophysics, represents a key research topic and expertise of our involvement in the European ALMA Regional Center (EU ARC), one of the three world centers of the international ARC infrastructure serving to support the science operations and further development of the ALMA Observatory. Our main contribution in this area in the period 2015-19 includes (i) Development of the Solar ALMA Observing Mode, its commissioning and science verification (our Institute was the leader of European consortium of the ESO project *Solar Research with ALMA*, carried out in 2014-17), (ii) User support for all European solar science observations with ALMA (from proposal preparation to data processing), and (iii) World-wide coordination and maintenance of the solar ALMA data reduction (QA2) procedures & documentation shared at http://wikis.alma.cl. Our activities in this field shall be described in detail below. In 2015 our participation in the project was institutionalized at the national level by acknowledging the status (and corresponding support) of *Large Research Infrastructures* to our ARC node by the Czech Government. Together with EST (see below) it is one of the two LRIs that ASI operates among total 48 LRIs in Czechia (https://www.vyzkumne-infrastruktury.cz/en/physic/eu-arc-cz/).

Large European solar optical telescopes – GREGOR & EST. Our participation in the GREGOR project (1.5 m solar telescope at Canaries, built and operated by consortium of German research institutions + ASI (CZ) + IAC (Spain); early science started in 2014) through the agreement with Leibnitz Institute for Astrophysics (AIP) in Potsdam continued during the last five years namely by its exclusive usage, guaranteed by our direct partnership with the project. Our Team members participated in many observing campaigns and the high-quality data acquired by the telescope contributed to the key results of our Team and were used in many of our publications (see above). The success of the spectro-polarimetric methods in revealing the detailed structure of the solar photosphere and chromosphere (incl. mag. fields) with the large instruments led to even larger international projects of giant solar telescopes. In Europe, a consortium of 18 countries (European Association for Solar Telescopes, Czechia represented by ASI belongs to 14 founding members) made an agreement on constructing and operating the 4m *European Solar Telescope* (EST). Its construction is currently in the advanced preparatory phase and the first light is expected in 2027. At the European level, the consortium is going to be institutionalized as ERIC (European Research Infrastructure Consortium), at the national scale our participation is covered by the LRI EST-CZ (https://www.vyzkumne-infrastruktury.cz/en/physic/est-cz/).

Space missions for solar & heliospheric research. At the beginning of 2020 the long-term international endeavor ended with its 'grand final' - the successful launch of the ESA/NASA space mission *Solar Orbiter.* Our Department was directly involved in the development of HW and SW parts for three of total 10 scientific instruments onboard (METIS, STIX, and RPW). The development goes on for the JUICE and Proba-3 ESA missions, where our department participates, too.

Fig. 4: Solar Orbiter – a mission to the Sun with our significant participation.

Research activity and characterisation of the main scientific results

Working group Physics of Hot Stars

Personnel. M.Kraus is the Head of the working group. Currently the group consists of: research fellows P. Koubský (em.), J. Kubát, B. Kubátová, and P. Škoda, postdocs T. Liimets, O. V. Maryeva, and P. Németh, and PhD students B. Doležalová and J. Fišák. Former members of the group during the last five years were: research fellows A. Aret, A. Kawka, S. Vennes, and V. Votruba; postdocs A. Hervé, M. Kourniotis, G. Maravelias, and D. Szécsi; and PhD students I. Pirković, A. Tichý, and S. Tomić.

Research results. *The main results of this group concern* theoretical and observational studies of massive hot stars, subdwarfs, and white dwarfs, theory and modelling of stellar atmospheres, winds, stellar ejecta, chemistry in circumstellar material, and transfer of radiation. Furthermore, the group is also focused on the research and education in data-oriented astronomy, i.e., astroinformatics. It is characterised by several complementing research directions. All citations refer to papers where Team members were involved.

<u>Stellar atmospheres, stellar winds, and their modelling</u>

Theoretical studies in this research field are mainly targeted at the development of sophisticated codes for stellar atmospheres and wind modelling and the investigations of physical mechanisms which govern different processes in stars and their surroundings. One of the main goals of the theoretical study of the research led by J. Kubát is to provide improved mass-loss rates of massive hot stars using their own developed sophisticated stellar atmosphere and wind codes including 3-D phenomena (such as non-sphericity and wind inhomogeneities, i.e., wind clumping). Furthermore, the research activities are focused on the development of codes which are able to calculate emergent spectra in different wavebands and which can be directly compared with observations. Based on such a comparison reliable values of stellar and wind parameters can be derived, in particular the mass-loss rates of massive stars in different evolutionary phases and different metallicity. The proper value of mass-loss rate is one of the main ingredients for stellar evolution modelling.

The group continued to work on the development of a hydrodynamic NLTE wind model code. This unique code enables a construction of a spherically symmetric wind model including a consistent calculation of the hydrodynamic structure based on the actual radiation force acting on wind matter, without a necessity to use unnecessary approximations (force multipliers). The most important steps of the code development were described in several papers (Krtička & Kubát 2017, A&A 606, A31; 2018, A&A 612, A20, and references therein). The code allows also external irradiation of the wind. Using this code it was analysed how strongly X-ray radiation from the secondary influences the wind of the primary in high-mass X-ray binaries (Krtička et al. 2015, A&A 579, A111; 2018, A&A 620, A150). Winds of high gravity stars were also analysed, namely of subdwarfs (Krtička et al. 2016, A&A 593, A101) and central stars of planetary nebulae (Krtička et al., 2020, A&A 635, A173). This work was led by and done in a close cooperation with colleagues from Masaryk University Brno. In a broader Team, two specific subwarfs (HD 49798 and BD+18 2647) were studied in detail with the help of our models (Krtička et al. 2019, A&A 631, A75) using data obtained during awarded observing time at the European Southern Observatory (ESO) spectrograph UVES@UT2.

The group also started a major update of their static spherically symmetric NLTE model atmosphere code by its transfer to modern versions of Fortran, which enabled a significant improvement in code performance. Recently, the group members succeeded to implement approximate treatment of atmospheric inhomogeneities and published the first results (Kubát & Kubátová 2019, ASPCS 519, 45). In a study of the effects of proper treatment of Rayleigh scattering in plane-parallel model atmosphere calculations it was found that it influences emergent radiation (Fišák et al. 2016, A&A 590, A95). The group members participated in several review papers, concerning X-ray influence on stellar winds (Krtička et al. 2016, AdSpR 58, 710) and structure of inhomogeneous winds (Oskinova et al. 2016, JQSRT 183, 100).

In addition to developing their own codes, the group members are also experienced in using similar stellar atmospheres and wind codes (e.g., TLUSTY, SYNSPEC, PoWR, and CMFGEN) as well as the stellar evolution codes (e.g., MESA) for analysing different types of stars. The important contribution of this type of research is a prediction of spectral appearance and spectral classification of the metal-poor (0.02 $Z_{\odot}$) chemically homogeneously evolving stars. It was found that a detection of a very hot star without almost any metal lines but with strong He II emission lines consistent with a very early-O type giant or supergiant will point to a strong candidate for a star resulting from chemically homogeneous evolution (Kubátová et al., 2019, A&A 623, A8). The synthetic spectra were computed using the Potsdam Wolf-Rayet (PoWR) atmosphere code while the stellar evolutionary sequences of low-metallicity ($Z \sim 0.02$ $Z_{\odot}$), fast-rotating massive star were computed using the Bonn evolutionary code (Szécsi et al. 2015, A&A 581, A15). Furthermore, stellar evolution and cluster hydrodynamics simulations were combined for the first time in a novel way to study the formation of globular clusters. This allowed drawing of an unprecedentedly complex picture on how and why supergiants can be responsible for abundance anomalies that we observe in globular clusters today (Szécsi & Wünsch 2019, ApJ 871, 20). The latter result was obtained in cooperation with Team 4.
We started a web-service to make stellar spectral analysis and atmospheric parameter inference for hot evolved stars available to a larger community. The service is a web interface to the classical NLTE model atmosphere code TLUSTY. Even though all procedures are public and well documented, such calculations are complex tasks from theory through informatics, which require tailored expertise. This is the major reason why some astronomers try to avoid such studies. With the framework provided by Astroserver (https://astroserver.org/) this procedure can be used on a user platform to produce publication-grade results with relatively little user personal efforts. The interface is also intended to help observers to quickly process spectra, as well as students to take their first step in quantitative stellar spectroscopy and learn spectroscopy with the TLUSTY code (Németh 2019, ASPCS 519, 117). The service, in its current form, is most suitable to fit hot subdwarf spectra, which is also reflected by the published results (e.g. Lei et al. 2018, ApJ 868, 70; Schindewolf et al. 2018, A&A 620, A36; Luo et al. 2019, ApJ 881, 7, Lei et al. 2019, ApJ 881, 135). A procedure for binary spectral disentangling was added to the service in 2019, which is heavily used in our hot subdwarf research. Future developments will extend the capabilities of the web-service to fit all types of stellar spectra.

<u>Massive stars in short-lived transition phases</u>

One more expertise of the group is the research of massive stars in short-lived transition phases. These phases are divided into several stellar classes: WR stars, LBVs, BSGs, B[e]SGs, YHGs, and RSGs. During all these phases, the stars display signs for highly dynamic atmospheres and envelopes, and expel a large amount of material, often in a series of eruptions. The ejected material accumulates in either circumstellar disks, shells, unipolar, bipolar or multi-polar nebulae. The research of massive stars in transition phases led by M. Kraus is focused on developing suitable methods to derive mass-loss values of these types of stars *and to investigate the chemical evolution, structure and dynamics of the ejected material*. The knowledge of the amount of mass a star loses within each phase of its life is of utmost importance for reliable predictions of the evolution and final fate of massive stars. Moreover, members of the group investigate physical mechanism(s) that can lead to enhanced mass-loss and trigger eruptions, as well as they analyse the chemical composition, the 3-D structure and dynamics of ejecta to uncover the mass-loss history of massive stars in transition.

The group combines the results from theoretical models with the information derived from observations. *Optical, infrared and radio* data are collected from 2- to 12-m telescopes, utilizing facilities at GEMINI North and South, *ESO's Very Large Telescopes, APEX Telescope, Nordic Optical Telescope, Gran Telescopio de Canarias, Southern African Large Telescope, 2.2-m MPI Telescope, 2.15-m CASLEO Telescope, and our Perek 2-m Telescope*. These data are supplemented with images from space missions such as the Spitzer Space Telescope, the Wide-field Infrared Survey Explorer, as well as with photometric data and light curves from various ground-based surveys (e.g., AAVSO, ASAS). In the past five years a number of objects in various categories in the Galaxy, the Large and the Small Magellanic Clouds (LMC, SMC), M31, and M33, were analysed. The most important results are highlighted here.

New ongoing eruptions for two LBVs in the Magellanic Clouds were identified. The stellar parameters that were derived for the stars before and during eruptions imply a drastic increase in luminosity during the outburst. Such a behaviour is not expected for a regular LBV S Dor cycle and imply that both stars experience an eruption accompanied by a large mass-loss (Campagnolo et al. 2018, A&A 613, A33). The variability of Romano's star in the nearby galaxy M33, which is an object in transition from an LBV to a WR star, was also followed and its current mass-loss rate was derived, which was found to be higher than ever before, with a highly increased outflow velocity (Maryeva et al. 2018, A&A 617, A51; 2019, Galaxies 7, 79). This star is surrounded by a compact but asymmetric envelope of ionized gas, a clear witness of a prior intense mass-loss (Maryeva et al. 2020, A&A 635, A201).

Based on optical and infrared spectroscopic and imaging data of a large sample of B[e]SGs, we discovered emission from molecules (TiO, CO, and SiO) arising in the close vicinity of the hot stars (Kraus et al. 2015, ApJ 800, L20; 2016, A&A 593, A112; Muratore et al. 2015, AJ 149, 13) and found that all objects are surrounded by a unique combination of multiple rings of atomic and molecular gas and dust (Aret et al. 2016, MNRAS 456, 1424; Maravelias et al. 2018, MNRAS 480, 320; Torres et al. 2018, A&A, 612, A113). These rings can be clumpy or smooth, and are found to be stable in case of single stars, for which we propose that planets or minor bodies might have formed in the disks, creating gaps and stabilizing the adjacent rings (Kraus et al. 2017, AJ, 154, 186). For B[e]SGs in binary systems, the rings are typically circumbinary and display high variability. We also performed a census of B[e]SGs and defined clear classification criteria for B[e]SGs in order to distinguish them from LBVs *as well as from massive pre-main sequence stars* (Kraus 2019, Galaxies, 7, 83). These criteria are based on specific emission features in the optical and near-infrared spectra, and on the disjoint loci of the objects in certain infrared color-color diagrams. The established criteria were used to classify a number of objects in our Galaxy and galaxies of the Local Group (Kourniotis et al. 2018, MNRAS 480, 3706; Condori et al. 2019, MNRAS 488, 1090; Arias et al. 2018, PASP 130, 114201, *Kraus et al. 2020, MNRAS, 493, 4308*).

The systematic photometric and spectroscopic monitoring of Galactic YHGs resulted in the discovery of a new outburst in one of them (Kraus et al. 2019, MNRAS 483, 3792). The detailed analysis revealed an enhanced photospheric pulsation activity prior to the outburst. *A decrease in the time intervals between outbursts was also noted, which was interpreted as an indication for an imminent major eruption. These studies further suggest that YHGs might evolve into B[e]SGs, linking these two phases (Aret et al. 2017, ASPCS 508, 239; Aret et al. 2017, ASPCS 510, 162).*

Pulsation activity was also investigated in a sample of BSGs. These objects display strong photometric and spectroscopic variability. Periodic variability in their winds was found, which correlates with previously identified variability periods (Haucke et al. 2018, A&A, 614, A91). The results suggest that radial pulsation modes might be responsible for the wind variability in the mid/late B-type stars. These radial modes might be identified with strange modes, which are known to facilitate (enhanced) a mass loss. Hence the observed wind variabilities were interpreted as due to a pulsation-triggered mass-loss (Kraus et al. 2015, A&A, 581, A75).

Massive stars are mostly born in double or multiple systems, and merging of two objects is a common phenomenon, altering the subsequent evolution of the merger remnant from single star evolution. Two merger remnants were discovered and analysed (Gvaramadze et al. 2019, MNRAS, 482, 4408). One of them is identified as high-velocity runaway O star with an associated horseshoe-shaped infrared nebula. The derived high stellar rotation speed can be best explained by a rejuvenated and spun-up binary product. The other object is the likely remnant of a super-Chandrasekhar mass merger of two carbon-oxygen white dwarfs. It was proposed that this object will produce a low-mass neutron star in the near future, accompanied by a high-energy transient and a fast-evolving supernova (Gvaramadze et al. 2019, Nature 569, 684).

Based on Perek 2m observations the group participated in an analysis of several delta Scuti stars in eclipsing binaries, which led to the determination of their effective temperature, surface gravity, and metallicity (Kahraman Aliçavuş et al. 2017, MNRAS 470, 915; 2017, AIPC 1815, 080013). The group also used data from the Perek 2m Telescope for a preliminary analysis of the quasi-WR star HD 45166 (Doležalová et al. 2019, ASPCS 519, 197). Furthermore, using the Perek 2m Telescope, we participated in an international campaign of observation of the bright Wolf-Rayet stars in Cygnus. It resulted in an international study of the variability of the star WR 134 (Aldoretta et al. 2016, MNRAS 460, 3407).

Subdwarfs and white dwarfs

White dwarfs are inevitably crucial objects to understand Galactic archaeology, stellar evolution, and supernovae, through which stellar astronomy is connected to cosmology. The research activity revolving around the late stages of stellar evolution in the group was led by A. Kawka and S. Vennes. With a particular focus on white dwarfs and hot subdwarfs, they developed and applied both observational and theoretical methods in their work.

The most significant scientific output in the research direction of white dwarfs was the discovery of the first bound remnant of a failed Type Ia supernova (Iax) event (Vennes et al. 2017, Science 357, 680). The intensive observational campaign and interpretation lasted for two years on world-class telescopes, including the 2.4-m Hiltner Telescope at the MDM Observatory (the USA), the 4.2-m William Herschel Telescope at La Palma (Spain), and the 8.2-m Gemini-North telescope (the USA). The object has a metal dominated atmosphere, therefore the analysis required new spectroscopic tools, that were developed within the Team by S. Vennes and A. Kawka.

Another significant output was the review paper of hot subdwarf binary populations (Kawka et al. 2015, MNRAS 450, 3514), where a thorough analysis based on collected literature data on all known hot subdwarf binaries was performed. Beyond the review, the paper discussed six new binaries that had been characterized for the first time using new measurements with MPG/FEROS as well as archival data. The study presented the companion mass distribution, which is important to the fine-tuning of future binary evolution models.

The close, super-Chandrasekhar double degenerate system NLTT 12758 consists of two CO white dwarfs of similar masses and ages, and one of the two components is highly magnetic. The magnetic white dwarf spins around its axis with a period of 23 minutes and they orbit around each other with a period of 1.15 days. Although the components of NLTT 12758 will not merge over a Hubble time, systems with very similar initial parameters will come into contact and merge thus undergoing either an accretion induced collapse to become a rapidly spinning neutron star (an isolated millisecond pulsar) or a Type Ia supernova explosion. The paper discusses the atmospheric, kinematic and evolutionary properties of the system (Kawka et al. 2017, MNRAS, 466, 1127). Spectroscopic observations obtained by XSHOOTER@UT3 at the ESO were used to analyse a cool metallic white dwarf NLTT 19868. Using a model atmosphere analysis its parameters together with metal abundances were derived (Kawka et al. 2016, MNRAS 458, 325).

Hot subdwarfs form a substantial fraction of low mass stars that experience an intermediate core helium-burning evolutionary phase before they become white dwarfs. They are at a major intersection on the evolutionary crossroad from the giant branch to the white dwarf sequence, at the hot end of the horizontal branch. These compact stars overwhelm white dwarfs in magnitude limited samples and dominate the Galactic disk populations of underluminous blue stars. Unlike white dwarfs, hot subdwarfs have more complex structures and peculiarities that require more sophisticated models, such as NLTE spectral synthesis.

The research focused on the spectroscopic investigations of hot subdwarfs using TLUSTY NLTE model atmospheres with a goal to process all available spectra and derive atmospheric parameters free of large systematics. The procedure must also include the analysis of composite binary spectra, due to the large binary fraction of hot subdwarfs. Extensions to process atmospheric chemical stratification and radiative interactions in close and compact binaries are underway. The former is important to derive an accurate luminosity function and mass distribution of hot subdwarfs, while the latter is necessary to be able to provide reliable stellar surface boundary conditions for seismic models. Gaia kinematic data has brought the necessary precision to calibrate the luminosity function and discover extremely peculiar objects that overlap with hot subdwarfs in the HRD (Vennes et al. 2017, Science 357, 680). This allowed us to develop automated tools we currently need to work with large data sets, such as SDSS and LAMOST spectra (e.g.: Luo et al. 2019, ApJ 881, 7; Lei et al. 2020, ApJ 889, 117). The methods, tools, and know-how acquired in these studies may prove to be essential in the near future when large spectroscopic surveys will collect massive data sets.

Be and shell stars

Be stars are B-type main sequence stars that show or sometimes in their recorded history showed emission lines, dominantly the hydrogen Hα line. Studies of this type of stars dominated the group output in the past. Although most of the active researchers in this field are retired now, their research continues. Several studies of individual Be stars were performed.

A successful observing ESO proposal (spectrograph SINFONI@UT4) led to a proper identification which component of the binary Be star 1 Del is the emission-line object (Kubát et al. 2016, A&A 587, A22). The pulsating Be star β CMi, possibly in a binary system, was reanalysed with a conclusion that its binary period cannot be confirmed (Harmanec et al. 2019, ApJ 875, 13). An analysis of photometric and spectroscopic observations of the binary system with a Be star, namely HD 81357, led to a determination of the period (33.77d), the mass ratio M1/M2 = 10, and a discovery that its low-mass secondary has to fill its Roche-lobe (Koubský et al. 2019, A&A 629, A105). Consequently, this system probably belongs to the family of stripped envelope stars.

Large data archives – Astroinformatics

The part of the group is involved in large data archives research and Astroinformatics, i.e., applications of machine learning and big data analysis in astronomy, including the Virtual Observatory (VO). This research is led by P. Škoda, V. Votruba (until the end of 2018), and several students from the Faculty of Information Technology of the Czech Technical University in Prague, the Faculty of Science of Masaryk University, Brno and the Technical University in Ostrava. The key research goals were divided into several main directions:

- Development of methods for finding Be stars using machine learning in millions of light curves, which were also incorporated in the pipeline of Gaia variability pipeline in the framework of Gaia CU7 (used in a number of papers of Gaia collaboration where V. Votruba and P. Koubský were co-authors, e.g. Holl et al. 2018, A&A 618, A30)
- Discovery of new emission line stars in big spectral surveys SDSS and LAMOST using deep learning and domain adaptation.
- Development of cloud-based infrastructure for machine learning of astronomical spectra.

- Development and implementation of standards of International Virtual Observatory Alliance, development of VO-compatible applications, setup of VO-compatible archives (Perek 2m Telescope spectra CCD700 based on SSAP protocol), remotely controlled DK154 (Danish 1,54-m Telescope at ESO) photometry telescope archive based on SIAP, SCS, and newly developed time-series protocol.

One of the main achievements are a definition of a new International Virtual Observatory Alliance (IVOA) standard for time series based on spare data cubes, which was presented at several IVOA Interoperability workshops and published as IVOA note (Nádvorník et al. 2017, IVOA Note 2017-12-15), and a modification of a widely used SPLAT-VO code for work with this standard (Šaloun et al. 2016, Springer Advances in Intelligent Systems and Computing 427, 373).

Members of the group participated in grants of the Czech Science Foundation, together with the Faculty of Mathematics and Physics of Charles University in Prague and the Technical University Ostrava. One of the results of this collaboration is the chapter about Big Data in complex systems, namely astronomy (Pokorný et al. 2015, Springer Studies in Big Data 9, 29). A subsequent project covering the research in Astroinformatics was the COST LD grant of the Ministry of Education, Youth and Sports led by P. Škoda. The results were presented at several Astronomical Data Analysis Software & Systems (ADASS) conferences (Škoda et al.2017, ASPCS 512, 689; 2019, ASPCS 521, 402) and IVOA workshops as well as at the conference Astroinformatics 2016 (Škoda et al. 2017, IAUS 325, 180).

Working group Extrasolar Planet Research

Personnel. The Head of the working group is P. Kabáth. Currently the working group consists of two postdocs, T. Klocová (currently on maternity leave) and M. Skarka, three PhD students M. Blažek, J. Šubjak, and M. Špoková.

Research results. *The main results of this group concern the radial velocities measurement and detection and characterization of exoplanet atmospheres, as well as studies of various types of pulsating stars, e.g. δ Sct or RR Lyrae variables. The members of the group are also engaged in space research activities and ground-based instrumentation.*

<u>Extrasolar planets</u>

The working group was officially established in May 2018. However, the first research results led by the members of the group were obtained earlier. Observations of a stellar flare on the planet host HD 189733 during a primary transit based on observations obtained using UVES@UT2 at the ESO were analysed in collaboration with the Hamburg Observatory (Klocová et al. 2017, A&A 607, A66). The analysis showed that the activity of an exoplanet host star can affect cores of a wide range of optical lines and must be taken into account when studying exoplanetary atmospheres.

The group had two main foci of research. The first topic was precise measurements of radial velocities for characterization of exoplanetary systems. Basically, spectroscopic measurements are used to characterize and validate newly reported exoplanet candidates. This topic includes the instrumentation and the space mission participation. The first highlight was in the field of instrumentation, i.e., resumption of operation of the Ondřejov Echelle Spectrograph (OES) for exoplanetary research (Kabáth et al. 2020, PASP 132, 035002). In the frame of the joint project with the Tautenburg Observatory the characterization of frequency of planets around A type stars from Kepler field was described (Sabotta et al. 2019, MNRAS 489, 2069). The Kepler-410 system was analysed in a collaboration led by colleagues from Slovakia (Gajdoš et al. 2019, MNRAS, 484, 4352). Radial velocities from three observatories (including observations using the OES spectrograph) were used, however, transit timing variations were not accompanied by radial velocity variations. In an international collaboration led by the group the first Transiting Exoplanet Survey Satellite (TESS) brown dwarf was confirmed using data from several observatories including the OES spectrograph at the Perek 2m Telescope, which contributed with a significant number of data points. The brown dwarf TOI-503b is physically extremely interesting as it sits directly in the Brown Dwarf desert (Šubjak et al. 2020, AJ, 159, 4).

The group also led and published the first-time detection of a δ Scuti like pulsator *with peculiar chemical composition caused by a magnetic field that is bound in a binary system with a red dwarf companion (Skarka et al. 2019, MNRAS, 487, 4230). It is the first detection of such an object*. The data set was mainly obtained with Perek 2m Telescope.

The second topic is the characterization of exoplanetary atmospheres, which is currently a hot topic of modern astronomy. An independent detection of sodium in two gas giant planets was reported (Žák et al. 2019, AJ 158, 120). Furthermore, the use of 2-m class telescopes for exoplanetary atmospheres research was evaluated (Kabáth et al. 2019, PASP 131, 085001).

RR Lyrae stars

The study of the RR Lyrae strars in our Team started in November 2017, when a new member of the group M. Skarka was employed. Since that time several papers about RR Lyrae stars have been published.

The most important result is the discovery of long-term cyclic period variations in pulsation period of RR Lyrae stars (Skarka et al. 2018, MNRAS, 474, 824). Such variations can easily be interpreted as the consequence of binarity via the Light-Travel Time Effect. This study revealed an alternative way that produces similar behaviour. We also identified new binary candidates with an RR Lyrae component which are extremely rare (Prudil et. al 2019, MNRAS 487, L1). In another paper, it was showed that the automatic routines are not suitable for the pre-processing of the Kepler/K2 data of RR Lyrae stars and a new estimation of the incidence rate of the Blazhko stars was estimated.

The last two papers dealt with the Oosterhoff dichotomy of RR Lyrae stars in the Galactic bulge (Prudil et al. 2019, MNRAS, 484, 4833 and MNRAS, 487, 3270; M. Skarka participated on the analysis and helped with the revision). All the work was performed in cooperation with colleagues from the Konkoly Observatory in Budapest and with the Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg.

Working group of High Energy Astrophysics

Personnel. The Head of the working group is M. Jelínek. The group consists of research fellows R. Hudec and V. Šimon; and a technician J. Štrobl.

Research results. The main results of this group concern the multi-spectral analysis of gamma-ray bursts (GRB), *other types of celestial high energy sources including various types of X-ray binaries* and cataclysmic variables (CV). The members of the group are also engaged in related space-based and ground-based instrumentation.

To obtain necessary high-energy observational data, the group was involved in high-energy satellite research, and also maintains the collaboration with a future ground-based facility bound to observe gamma-rays from surface – Čerenkov Telescope Array (CTA), which is being built at two sites, La Palma and Paranal. CTA now counts with three robotic telescopes FRAM built and operated in collaboration between the Institute of Physics of the Academy of Sciences of the Czech Republic and the group of High Energy Astrophysics. The group has also been operating two relatively small robotic telescopes on the ground of the Ondřejov Observatory since 2000 (25 cm) and 2004 (50 cm). The role of these telescopes is to complement high energy observations with original optical data for both GRB and CV. These objectives complement well, as the GRBs require a small amount of rapid-response time, while CVs occupy the long-term programme.

The GRB observations are typically promptly reported through the Gamma-ray Coordinates Network (GCN). During the past five years, more than a dozen such Circulars were issued with successful minute-timescale responses of robotic telescopes to the satellite GRB triggers. The summary of GRB observations obtained by the BOOTES-system in collaboration with Spain was elaborated in form of a large article, which includes 71 GRB follow-ups providing optical afterglow detections in 23 cases (Jelínek et al. 2016, Advances in Astronomy 2016, 192846). The analysis of seven faintest γ-ray burst afterglows detected by the 50 cm telescope in Ondřejov was recently presented as well (Jelínek et al. 2019, AN 340, 622).

We also presented studies of the long-term activity of various types of binary X-ray sources (systems with an accreting compact object): the intermediate polar GK Per (Šimon 2015, A&A 575, A65); the accreting neutron star Her X-1 (Šimon 2015, AJ 150, 3); the polar AM Her (Šimon 2016, Ap&SS 361, 235; Šimon 2016, MNRAS 463, 1342); a very luminous nova-like binary QU Car (Šimon 2017, AN 338, 696); the post-nova X Ser (Šimon 2018, A&A 614, 141) and a dwarf nova DT Oct (Šimon & Edelmann 2019, AstBu 74, 490).

The group also invested a considerable effort into the observations of DG CVn, which resulted in two related studies (Caballero-García et al. 2015, MNRAS 452, 4195; Šimon 2017, Rev. Mex. Astron. Astrophys. 53, 59). An important part of the group's work is the operation, improvements and maintenance of the robotic telescope instrumentation. For one of the devices, this effort was recently summarized and presented by Štrobl et al. (2019, AN 340, 633).

The group also specializes in the study of archival photographic images, both direct and spectral, and participates actively in the rescue of valuable old observations stored in the archives of various observatories on glass photographic plates and negatives. Archival data are used to monitor the long-term behaviour of high-energy radiation sources and to follow and interpret their physical nature. This enables to study the activity of such sources on very long time-scales. These data were applied, e.g., in analyses a blazar OJ 287 (Valtonen et al. 2016, ApJ 819, L37; 2019, ApJ 882, 88; Dey et al. 2018, ApJ 866, 11).

The group also contributed to the efforts of detecting gravitational waves by observing with local telescopes (Abbott et al. 2016, ApJS 225, 8, Abbott et al. 2016, ApJ 826, L13).

In the research led by R. Hudec the group also participated in the design and the development of new innovative space experiments with an emphasis on X-ray optics, telescopes, and monitors (e.g., Hudec et al. 2017, SPIE 10569, Hudec et al. 2017, SPIE 10563). The group is also involved in data analyses related to ESA Gaia satellite (e.g., Šimon et al. 2017, Experimental Astronomy 44, 129). The group is also involved in the design of astrophysical payloads on nano and cube satellites (e.g., Tichý et al. 2015, Baltic Astronomy 24, 242, Remisova & Hudec 2017, SPIE 10562, 105620U).

The group regularly organizes international conferences and workshops (AXRO and IBWS), and participates in the organization of large international conferences such as SPIE Europe, Frascati workshop on Multispectral behaviour of cosmic high-energy sources, and international conferences on Frontier objects in astrophysics.

Working group Operation and Development of the Perek 2m Telescope

Personnel. The Head of the working group is M. Šlechta. The group consists of three technicians, L.Řezba, J. Sloup, and R. Novotný. Former technicians were L. Kotková, J. Honsa and J. Fuchs.

The main task of this working group concerns the maintenance and the upgrading of the Perek 2m Telescope in Ondřejov. The Perek 2m Telescope installed in Ondřejov is the main instrument for stellar and since recently also for exoplanetary research in the Czech Republic. The telescope is equipped with single order and echelle spectrographs, both placed in the coudé focus. The single order spectrograph can be used in the first and second spectral orders with a resolving power of 12000 in the Hα spectral region (first order) while the echelle spectrograph has a resolving power of 40000 around the Hα line. The single order spectrograph displays 47.5 nm in the first and 23.8 nm in the second spectral order. Both spectrographs are equipped with CCD chips cooled by liquid nitrogen.

The single order spectrograph operates in the first and the second spectral orders. The first order is used in the red part of the spectrum, from 5100 to 8900 Å. The second order is used in the blue part, between 4000 and 5100 Å. For the light dispersion we use the Bausch&Lomb grating with 833 gr/mm. The resolving power is 12000 in the Hα spectral region (around 6563 Å). For the detection of the light we use the CCD chip PyLoN 2048x512BX, E2V 42-10 BX, pixel size 13.5 μm, cooled by liquid nitrogen to −115ºC. The spectrograph is used mainly for studies of hot stars. The main advantage is that it depicts a wide interval of wavelengths (475 Å in the Hα spectral region) with uniform S/N.

The resolving power of the Ondřejov Echelle Spectrograph (OES) spectrograph is 40000 in the Hα spectral region. It depicts a lot of short spectral orders. One order covers 85 Å (in the near UV region) up to 120 Å (in the near IR region). The spectrograph is equipped with two dispersion elements. The first dispersion element: grating, 55gr/mm, blaze angle 69 deg, made by Richardson Grating Laboratories; the second dispersion element: equilateral prism, apical angle 55 deg, glass Schott LF5, made by “Vývojová optická dílna” Turnov (now TopTec Turnov), part of the Institute of the Plasma Physics of the Czech Academy of Sciences. The light is depicted on the CCD chip Versarray 2048B, EEV 2048x2048, EEV 42-10-1-36B, pixel size 13.5 μm, cooled by liquid nitrogen to −110ºC. As the spectrograph depicts short spectral orders, it is used mainly for a precise measurement of radial velocities. It can also be used for study of narrow lines profiles because the continuum can be detected just around narrow lines. An example of the echellogram see Figure 1.

For a safe operation of the telescope the meteorological station is used to follow humidity while an all sky camera is used to monitor clouds. The operation, service works, and upgrades of the telescope are carried out by three technicians who also serve as night assistants.

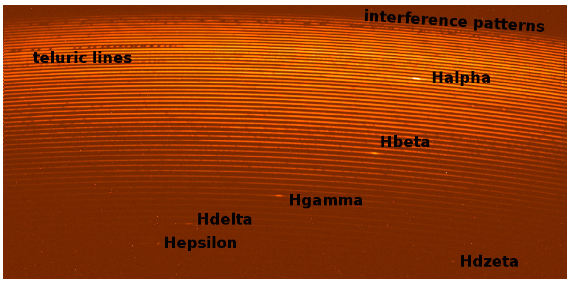

Fig. 1: The echellogram of the eruptive star AD Leo, spectral type M4.5Ve and magnitude V=9.4 mag.

During the last five years, the group performed upgrades of the telescope concerning the reliability and safety of the operation and also the optical configuration and efficiency of the telescope. The diesel backup power supply for elimination of a possible electricity blackout was installed in 2015. It allows an independent closing the dome shutter during an electricity failure to prevent effects of storms or any other weather calamities. The power supply also serves for permanent operation of the CCD chips which should not be under-cooled.

In 2016, a regular maintenance operation, the recoating of the main mirror was done in the company 4H-Jena engineering, which inherited the equipment from the company Carl-Zeiss Jena, who finished building the telescope in 1967. However, during the works in the 4H-Jena engineering company, a part of the mirror was damaged. The company succeeded to fix the problem and the mirror can be used again, however, the effective surface of the mirror was reduced by about 6% of total mirror area. Despite this, the telescope was successfully put back into operation in 2017.

The most significant and fundamental upgrade of the telescope during the last decades was performed by the group in 2019. The optical configuration was completely changed, which led to an increased efficiency of the optical system. Previously, the light was reflected to the coudé spectrograph with a system of mirrors. However, the reflecting surfaces slowly degenerate with time and it leads to an exponential decrease of the total efficiency. The main part of the upgrade was putting the optical fibres from the primary focus to the coudé room, where the spectrographs are placed. As a result, only one reflecting surface (i.e., the 2-m primary mirror) is present instead of four mirrors, used originally. With this upgrade of the telescope, higher efficiency and extension of the observational limits were achieved. The possibility of observing fainter objects broaden the number of observing programmes which can be performed with the Perek 2m Telescope.

Besides the upgrade of the optics of spectrographs, in addition, the field of view in the primary focus is used and a photometric Mark2 3200 camera (Moravian Instrument) for direct imaging is installed there now. One example of the image taken with this camera is shown in Figure 2. The diameter of the field of view is 7 arcmin. Currently, the photometric camera is equipped with *u, g, r, i,* and *z* collar filters corresponding to Sloan sky survey. It can also be equipped with narrow-band filters, for instance for the investigation of planetary nebulae. The camera is also a proper device for monitoring of optical counterparts of γ-ray bursts object which are the subject of research of the High Energy Astrophysics working group, which is a part of the Team.

Fig. 2: The composite image of the nearby starburst galaxy, Messier 82 (M82) taken with Mark2 3200 camera using u', g', r' and z' collar filters.

The Perek 2m Telescope served as an observing tool for a number of projects, led partly by local scientists and partly by colleagues from collaborating institutes. The projects led by local scientists were mentioned in the parts devoted to working groups of Physics of Hot Stars and Extrasolar Planet Research. Here we shall mention the projects led by scientists outside the Team. As the telescope can offer observations which span over longer time intervals, it was mainly used for studies of binary stars and multiple stellar systems. The long-term observations are essential for this type of projects and are done mostly in collaboration with colleagues from the Team, who serve as observational astronomers and also provide their experience in data processing and analysis.

There is a number of binary and multiple stellar systems observed using the Perek 2m Telescope. Observations obtained with the Perek 2m Telescope contributed to studies of an eclipsing binary BD+36°331 (Kıran et al. 2016, A&A 587, A127), a triple system V746 Cas (Harmanec et al. 2018, A&A 609, A5), triple systems V348 And and V572 Per (Zasche et al. 2019, AJ 158, 95), triple systems V773 Cas, QS Aql, and BR In (Zasche et al. 2017, AJ 153,36), and a quadruple system ξ Tau (Nemravová et al. 2016, A&A 594, A55). Some members of the enigmatic class of B[e] stars we observed as well, namely MWC 728 (Miroshnichenko et al. 2015, ApJ 809, 129), HD 50138 (Jeřábková et al. 2016, A&A 586, A116), and several B[e] candidates (Arias et al. 2018, PASP, 130, 114201). Archival spectra from the Perek 2m Telescope were used to supplement interferometric analysis of the eclipsing interacting binary β Lyr (Mourard et al. 2018, A&A 618, A112).

Research activity and characterisation of the main scientific results

Group of Meteor Physics

The analyses of important individual bolides leading to meteorite falls

The Group of Meteor Physics is a world leading group in observations of bright bolides and interpretation of bolide data. The instrumentally observed meteorite falls represent a special category. The scientific value of the data increases when both the bolide and the corresponding meteorites can be analysed. The number of instrumentally observed meteorite falls has continued to increase in the recent years also thanks to our observations and/or computations. At the moment, there are about 35 instrumentally observed falls worldwide. The number became somewhat blurred since there are cases where some instrumental data about the bolide exist but the data or the involved analyses are poor and the results are therefore not very reliable. In any case, our group participated in the analyses of more than half of these cases and we believe that our results belong to the most reliable ones. It is especially true for the cases when the bolide was observed by our own dedicated EN cameras and radiometers. In the period 2015 – 2019, the meteorites Stubenberg, Hradec Králové, and Renchen were recovered on the basis of our observations and analyses. Without our computation of the meteorite strewn field, these meteorites would remain hidden in the fields and forests of the central European landscape. The same case was the Žďár nad Sázavou meteorite, which fell down at the end of 2014 and where very detailed data enabled us to analyse the atmospheric flight thoroughly. The final paper was accepted in December 2019 and published at the beginning of 2020. The analysis of the Križevci meteorite fall of 2011 was published in 2015. We also determined the trajectory and orbit of the Ejby meteorite, which fell down in 2016 in Denmark. Casual records were combined with our radiometric curve. Finally, the fall of the carbonaceous meteorite Maribo (2009, also Denmark) was reanalysed and modelled using three fragmentation models.

There were about two dozen meteorite dropping bolides observed by EN cameras between 2015 – 2019, where we initiated or performed by ourselves unsuccessful meteorite searches. These were mostly smaller events with limited number of expected fragments on the ground. Although meteorites were not recovered, the atmospheric fragmentation was studied in detail. A paper about strengths of ordinary chondritic meteoroids, based on both recovered and unrecovered meteorite falls, was prepared and submitted for publication.

Among the papers already published on the topic of meteorite falls, the most important are:

- Borovička J., Spurný P., Šegon D., Andreić Ž., Kac J., Korlević K., Atanackov J., Kladnik G., Mucke H., Vida D., Novoselnik F.: The instrumentally recorded fall of the Križevci meteorite, Croatia, February 4, 2011, Meteoritics & Planetary Science 50, 1244–1259 (2015)

The Križevci fall was the 19th instrumentally recorded meteorite fall in history. All available camera records were analysed to obtain a reliable atmospheric trajectory, orbit, and initial mass. Moreover, the radiometric light curve from Martinsberg enabled

us to model the meteoroid atmospheric fragmentation. It was shown that the recovered meteorite was the only sizeable fragment that reached the ground. This work added a valuable piece among still rare class of meteorites with known orbits.
All final analysis and the paper writing were done by members of our Team. The photograph and radiometric record from the camera in Martinsberg, operated by our Team in collaboration with Austrian colleagues, were very important to characterize the bolide. The co-authors from Croatia and Slovenia provided their camera records. The Croatian team recovered the meteorite.

- Spurný P., Borovička J., Baumgarten G., Haack H., Heinlein D., Sørensen A.N.: Atmospheric trajectory and heliocentric orbit of the Ejby meteorite fall in Denmark on 6 February 2016, Planetary and Space Science 143, 192-198 (2017)

The Ejby meteorite fall occurred in the Copenhagen suburbs of Denmark on February 6, 2016 and raised attention of many inhabitants in large areas of NW Europe. We collected available casual optical records and combined them with our own radiometric records. Thanks to our rich experience with the analysis of these data, we were able to describe this extraordinary bolide reliably and bring a complete picture of its atmospheric trajectory and fragmentation, photometry and heliocentric orbit.
All analysis work and vast majority of the paper writing was done by members of our Team. German and Danish colleagues provided us with casual optical records, calibration of the video record and wind profile model. Danish colleagues also collected the meteorites.

- Borovička J., Popova O., Spurný P.: The Maribo CM2 meteorite fall—Survival of weak material at high entry speed. Meteoritics & Planetary Science 54, 1024-1041 (2019)

The recovery of the rare carbonaceous Maribo meteorite was a surprising and very important event. By analysing the available bolide data, we confirmed the high entry speed of 28 km/s which we had previously derived and which also corresponded well to values derived by other authors. We also refined the trajectory and orbit. To explain how such fragile material can survive high entry speed, we applied three different fragmentation models to our radiometric light curves. We found that internal cracks, which weaken ordinary chondrites, are not important for carbonaceous chondrites. Although carbonaceous chondrites are intrinsically weaker, both types therefore reach similar fragmentation strengths.
The radiometric light curves were obtained by our Team. We computed the bolide trajectory and orbit and applied one of the fragmentation models. O. Popova applied the other two models and contributed, together with us, to the interpretation of the results.

- Spurný P., Borovička J., Shrbený L.: The Žďár nad Sázavou meteorite fall: Fireball trajectory, photometry, dynamics, fragmentation, orbit, and meteorite recovery. Meteoritics & Planetary Science 55, 376-401 (2020)

Fig. 1: The Žďár nad Sázavou fireball. A section from an all-sky image taken by DAFO at Veselí nad Moravou.

The main exceptionality of this case consists of a detailed analysis of a high number of high-resolution instrumental records (both photographic and radiometric) taken by our automated cameras (both digital and analog) in the Czech part of the EN. Thanks to our experience how to analyse such an unusually large amount of high-quality data from dedicated instruments, we were able to obtain detailed, reliable, and precise results concerning atmospheric trajectory, photometry, dynamics, and heliocentric orbit of the Žd'ár bolide. On top of that, we described in detail its fragmentation scenario and predicted the impact area for all sizes of meteorites. The reality exactly confirmed our predictions because all meteorites were found in the predicted areas and their masses well corresponded to the predicted ones. This is the best proof of a correct interpretation of our observations. The_Žd'ár nad Sázavou bolide and meteorite fall was the first recorded by the newly modernized Czech part of the EN and validated the correctness of this modernization of our instrumental facilities and their background as well. The Žďár nad Sázavou fall belongs to the most reliably, accurately, and thoroughly described meteorite falls in history.

This work was entirely carried out by members of our Team.

Physical properties and composition of meteoroids; their ablation, radiation, and fragmentation in the atmosphere

Revealing the structure and composition of meteoroids from meteor observations is in fact the main goal of the Group. Although meteorites provide the "ground truth", their delivery is only possible from meteoroids, which are large enough and strong enough so that their part can survive the atmospheric passage. Bolide observation provide data on meteoroids, which are large but too fragile or have a too high entry speed to drop meteorites. The observation of fainter meteors provides the information about smaller meteoroids (less than one centimetre). Small meteoroids can, generally, have different sources than large ones.

Physical properties are studied on the basis of observed light curves, decelerations and morphologies (presence of wakes and individual fragments) of meteors. Further information is extracted from meteor spectra, which are also used to reveal chemical composition of meteoroids. Almost all used data are from our own instruments. The reduction methods and the fragmentation models used to fit the data were also developed by our Group.

The topical issues of the last five years ranged from a unique individual superbolide, over stream meteoroids of common origin (the Taurids) to a general study of small meteoroids. The special attention was paid to peculiar iron meteoroids. The most important papers published as of March 2020 are:

- Borovička J., Spurný P., Grigore V., Svoreň J.: The 7 January 2015, superbolide over Romania and structural diversity of meter-sized asteroids. Planetary and Space Science 143, 147-158 (2017)

The trajectory, the orbit, and the atmospheric fragmentation behaviour of a very bright superbolide over central Romania were determined using the data from two bolide cameras in Slovakia, one in Czechia (both photographic and radiometric records) and five carefully calibrated casual video records from Romania. The bolide was so bright that it was detected from the orbit by the US Government sensors. The reported speed was, however, found to be wrong. The orbit was asteroidal but the fragmentation pattern was found very untypical. The meteoroid resisted until the dynamic pressure of 1 MPa but then disrupted completely. We concluded the meteoroid represented a new type of asteroidal material not contained in meteorite collections.
All analysis and the paper writing were done by members of our Team. The photographs and the radiometric records from the cameras in Stará Lesná, which are a part of our network and are operated in collaboration with Slovakian colleagues, were very important to characterize the bolide. The co-author from Romania provided calibration photos for the casual video records.

- Borovička J., Berezhnoy A.A.: Radiation of molecules in Benešov bolide spectra. Icarus 278, 248-265 (2016)
- Berezhnoy A.A., Borovička J., Santos J., Rivas-Silva J.F., Sandoval L., Stolyarov A.V., Palma A.: The CaO orange system in meteor spectra. Planetary and Space Science 151, 27-32 (2018)

The photographic spectrum of the Benešov superbolide obtained at the Ondřejov Observatory in 1991 is still unique in many aspects. It is the only spectrum produced by a meter-class meteoroid. In the first paper we concentrated on the analysis of molecular radiations. The spectra of CaO, AlO, and MgO observed in Benešov were not detected in any other meteor spectrum. We compared the intensities of these bands with FeO along the trajectory and compared them with theoretical calculations. Non-equilibrium effects, e.g. the difference between rotational and vibrational temperature of AlO, were found. CaO and FeO could not be analysed in detail, because their molecular constants, especially transition probabilities, are not well known. The second paper was devoted specially to the analysis of CaO electronic transitions and the comparison of the synthetic spectrum with the Benešov spectrum.
The Benešov spectrum was obtained by our Team. J. Borovička extracted and calibrated the molecular spectra and computed rotational and vibrational temperatures of AlO. A. Berezhnoy provided theoretical calculations of molecular band intensities and organized the work on the second paper. Other authors of the second paper contributed with the theoretical investigation of CaO molecular states.

- Vojáček V., Borovička J., Koten P., Spurný P., Štork R.: Catalogue of representative meteor spectra. Astronomy and Astrophysics 580, A67 (31pp.) (2015)

- Vojáček V., Borovička J., Koten P., Spurný P., Štork R.: Properties of small meteoroids studied by meteor video observations. Astronomy and Astrophysics 621, id. A68 (21pp.) (2019)

The catalogue of representative meteor spectra provided the first database of low-resolution spectra of relatively faint meteors. It was based on our decade-long video observations. Spectra were divided into spectral types and compared with orbital types. The effect of velocity on line intensities was pointed out. The catalogue was well received by the community and serves as a valuable source of information for meteoritical works.

The combination of spectral and orbital properties of small meteoroids with the modelling of their erosion in the atmosphere provided a unique insight into the population of small debris of the Solar system. We showed that the physical properties are influenced both by the origin and by the evolution of the orbit. Iron meteoroids on cometary orbits were found, supporting the idea of large-scale mixing in the early solar system. Early ablation of sodium was typical for bodies with small grains. Bodies depleted in sodium were generally stronger and lacked the finest grains. All work was done entirely by members of our Team, including observation, analysis, and modelling by our own methods.

- Čapek D, Borovička J.: Ablation of small iron meteoroids-First results. Planetary and Space Science 143, 159-163 (2017)
- Čapek D., Koten P., Borovička J., Vojáček V., Spurný P., Štork R.: Small iron meteoroids. Observation and modelling of meteor light curves. Astronomy and Astrophysics 625, id. A106 (17pp.) (2019)
- Vojáček V., Borovička J., Spurný P., Čapek D.: The properties of cm–sized iron meteoroids. Planetary and Space Science 182, id. 104882 (7 pp.) (2020)

Iron meteoroids can be distinguished by the presence of iron lines and by the absence of usually bright lines of Na, Mg, Ca in their spectra. We first studied a population of faint iron meteors characterized also by low beginning heights and often unusual light curves with a rapid increase of the brightness near the beginning. We developed three numerical models of their ablation based on three different physical processes. We found that the scenario of immediate removal of liquid iron from the meteoroid surface as droplets with a Nukiyama-Tanasawa size distribution is able to reproduce the data. Dedicated video observations of faint iron meteoroids were performed and the model

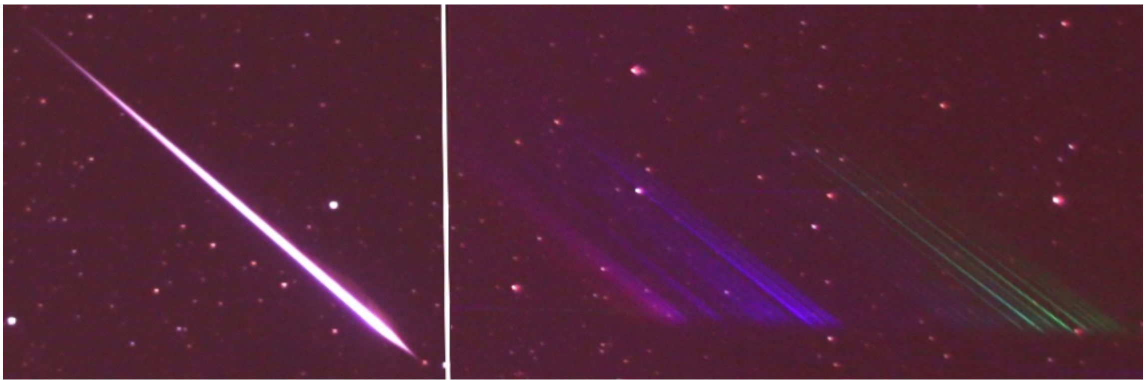

Fig. 2: Iron fireball (left) and its spectrum (right) captured by a SDAFO (Vojáček et al. 2019).

was applied to 60 meteors. The model was able to adequately describe most of the light curves. For an individual meteor, the model allowed us to estimate the initial mass, mean drop size, and luminous efficiency. The fact that mass and luminous efficiency can be estimated independently is a unique property of the model.

We then collected fireballs with iron spectra observed by the newly developed Spectral Digital Autonomous Fireball Observatories. A sample of 9 iron meteoroids with diameters about 1 – 4 cm was studied. The orbits were asteroidal and similar to those ones of small iron meteoroids. Surprisingly, using classical methods of fireball classification, these fireballs were classified, at least formally, as fragile bodies comparable in strength to cometary meteoroids. The ablation model for small meteoroids was not directly applicable. The erosion model was able to fit the light curves by manually adjusting erosion parameters. To describe the sudden drop at the end of the light curve, it was necessary to increase the erosion coefficient progressively and decrease droplet masses along the trajectory.

All work was entirely carried out by members of our Team.

- Koten P., Čapek D., Spurný P., Vaubaillon J., Popek M., Shrbený L.: September epsilon Perseid cluster as a result of orbital fragmentation. Astronomy & Astrophysics 600, id. A74 (5pp.) (2017)

A bright fireball was observed above the Czech Republic on 9 September 2016. Moreover, the video cameras at two separate stations recorded additional eight fainter meteors flying on parallel atmospheric trajectories within less than 2 seconds (see Figure. 4 below). All the meteors belong to the September epsilon Perseid meteor shower. The observed group of meteors was interpreted as the result of the orbital fragmentation of a bigger meteoroid. The fragmentation happened no earlier than 2 or 3 days before the encounter with the Earth at a distance smaller than 0.08 AU from the Earth. In the past, such clusters were occasionally observed among very active meteor showers. As the September epsilon Perseid shower is not such a case, the result is exceptional.

Four of six authors including the corresponding author are members of our Team. M. Popek (IAP CAS) provided us with one video record and J. Vaubaillon (France) participated in modelling of the orbital fragmentation.

- Borovička J., Spurný P.: Physical properties of Taurid meteoroids of various sizes. Planetary and Space Science 182, id. 104849 (8 pp.) (2020)

The origin of the Taurid complex is still debated. In addition to comet 2P/Encke, various asteroids were proposed to be members of the complex and thus possible parent bodies of Taurid meteoroids. Previous work suggested that meteorite dropping fireballs can be encountered among Taurids. We used a well-defined orbital sample of 16 Taurid fireballs with detailed radiometric light curves and modelled their atmospheric fragmentation. The sample represented meteoroids of initial masses from 8 g to 650 kg (diameters 1–70 cm). It was found that the majority of Taurid material has a very low strength of less than 0.01 MPa and a density less than 1000 kg/m^3. Stronger material up to 0.3 MPa is present as well and forms small inclusions in large bodies or exists as small (cm-sized) separate bodies. These properties strongly suggest a cometary origin of Taurids. The reported strong fireballs were most probably interlopers of different origin. This work was entirely carried out by members of our Team.

Orbital studies

Besides the information about their atmospheric behaviour, our instruments also provide data on heliocentric orbits of all observed fireballs and meteors. Some of our work is devoted primarily to orbital studies. It concerns the extraordinary activity of meteor showers, some regular meteor showers, as well as individual meteors of special interest. In the evaluated period we published fundamental papers on a fireball on the Earth-bound orbit, the first of its kind, and on the discovery and detailed description of a new branch of Taurid meteoroid stream.

- Clark D.L., Spurný, P., Wiegert P., Brown P., Borovička J., Tagliaferri E., Shrbený L.: Impact detections of temporarily captured natural satellites. The Astronomical Journal 151, id. 135, (15pp.) (2016)

Based on the observation of the unique bolide on January 13 2014 by the cameras of our fireball network, it was proved that it is the first such case in the world where the meteoroid before its collision with Earth was temporarily captured as a natural satellite of Earth (Minimoon). This exceptional result was only possible to achieve thanks to very precise data. Such an accuracy is crucial for a reliable backward integration of the meteoroid orbit and the recognition of its exceptional history.

This is common work of our Team and the team from University of Western Ontario ((UWO). The instrumental data on the bolide and its analysis was obtained by our Team. The backward integration was performed by the UWO team. Both teams interpreted the results and contributed to their parts of the text.

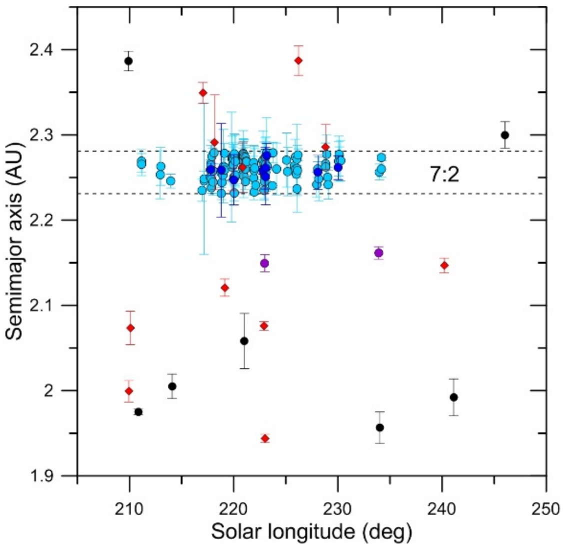

Fig. 3: Plot of semimajor axes vs. solar longitude for 2015 Taurid fireballs showing a tight clustering of most orbits in the 7:2 resonance with Jupiter.

- Spurný P., Borovička J., Mucke H., Svoreň J.: The discovery of a new branch of the Taurid meteoroid stream as a real source of potentially hazardous bodies. Astronomy and Astrophysics 605, id. A68 (25pp.) (2017)

Based on an accurate analysis of 144 Taurid fireballs captured in 2015 by our fireball network we discovered that this enhanced activity of fireballs was caused by a well-defined orbital structure of bodies belonging to the Taurid complex. We proved that it also contains large bodies up to at least hundreds of meters. It is for the first time when a real source of potentially hazardous bodies that can cause a regional or even continental disaster on Earth was identified and described.

The vast majority of used records, all analysis and the paper writing were done by members of our Team. The contribution of Slovak and Austrian colleagues consisted only of the use of photographic and radiometric records for some Taurid fireballs from one camera in Austria and one in Slovakia, which are a part of our network and are operated in collaboration with these colleagues of ours. The paper was chosen for the official press release of the A&A journal.

- Abedin A., Spurný P., Wiegert P., Pokorný P., Borovička J., Brown P.: On the age and formation mechanism of the core of the Quadrantid meteoroid stream. Icarus 261, 100-117 (2015)

The Quadrantid meteor shower is among the strongest annual meteor showers and it is unusual as for its very short duration around the maximum activity, its recent onset and an unusual parent body, asteroid 2003 EH1. For the first time we used the data on high precision photographic Quadrantids, equivalent to gram–kilogram size, to constrain the age of the core of the stream. According to our results, from the backward integrations, the most likely age of the Quadrantids is between 200 and 300 years.

This is common work of our Team and the team from University of Western Ontario ((UWO). The instrumental data on the used Quadrantids fireballs and their analysis were performed by our Team. The backward integration was performed by the UWO team. Both teams participated in the interpretation of the results and the contribution to their parts of the text.

- Shrbený L., Spurný P.: September epsilon Perseids observed by the Czech Fireball Network. Astronomy & Astrophysics 629, A137 (2019)

We presented 25 photographic fireballs belonging to the September epsilon Perseid (SPE) meteor shower observed by the Czech part of the European Fireball Network in 2013–2017. An exceptionally high activity of bright photographic fireballs was observed in 2013, while a lower activity, but still higher than in other years, was observed in the period of 2015–2017. Physical properties of these SPE fireballs were studied and compared to other meteor showers. A corrected geocentric radiant of the 2013 outburst fireballs was determined and can be used for the confirmation of future outbursts in 2026 and 2030, as predicted by another team. On the basis of determined heliocentric orbits the parent body of the shower is an unknown long-period comet on a retrograde orbit with an orbital period of the order of a thousand years. This work was entirely carried out by members of our Team.

- Koten P., Borovička J., Vojáček V., Spurný P., Štork R., Shrbený L., Janout P., Fliegel K., Páta P., Vítek S.: Activity profile, mass distribution index, radiants, and orbits of the 2018 Draconid meteor shower outburst. Planetary and Space Science 182, id. 104871 (9 pp.) (2020)

Following the successful observation and analysis of the 2011 Draconid meteor shower outburst, another such an event was predicted by the theoretical modellers for 8 October 2018. Using a variety of video and photographic cameras covering a broad range of magnitudes, the outburst was successfully observed by us. The main peak was found at 23:07.5 ± 0:05 UT, in a good agreement with other reports as well as with the predictions. Two other sub-peaks or enhancements of the activity were detected later in the night. The maximum flux of meteoroids was 0.033 ± 0.007 meteoroids km^{-2} h^{-1} [M_V> +6.5], equivalent to ZHR = 140 ± 30 which is higher than the majority of the models predicted. The analysis of radiants, mass distribution index evolution and the comparison with other experiments suggest that the later activity was probably caused by a mixture of different trails of the stream which were more dispersed. The flux of the meteoroids was three to four times smaller in comparison with the 2011 Draconid outburst. Heliocentric orbits of individual meteoroids were also reported.

The result was obtained mostly by members of our Team. The co-authors from the Czech Technical University participated in the development of the MAIA cameras.

- Hajduková M., Koten P., Kornoš L., Tóth J.: Meteoroid orbits from video meteors. The case of Geminid stream. Planetary and Space Science 143, 89-98 (2017)

In this joint work with Comenius University in Bratislava, we studied the orbits of Geminids and showed that in most video databases (except ours) the initial speed of meteors is systematically underestimated.

Books and reviews

The expertise of the Team members is reflected in the invitations they get to present lectures and contribute to books. A part of the invitations was related to the Chelyabinsk superbolide of 2013 (the asteroid largest impact of the last century). Our Team contributed significantly to the description of that event. J. Borovička was invited to present a lecture about Chelyabinsk during the IAU General Assembly in 2015 and at the Erice (Italy) international school in 2017. The first lecture was published in the proceedings from the IAU (Borovička J.: The Chelyabinsk event. In: Astronomy in Focus, Volume 1, Focus Meeting 9, Ed.: P. Benvenuti, Proceedings of the International Astronomical Union, Volume 11, Issue A29A, 247-252, 2016) and the second lecture was published as a chapter in the book (Borovička J.: The trajectory, structure and origin of the Chelyabinsk impactor. In: Hypersonic Meteoroid Entry Physics, Eds.: G. Colonna, M. Capitelli, and A. Laricchiuta, IOP Series in Plasma Physics, IOP Publishing, Bristol, UK, pp. 2-1 - 2-11, 2019). We also published a catalogue of video records related to the Chelyabinsk event (Borovička J., Shrbený L., Kalenda P., Loskutov N., Brown P., Spurný P., Cooke W., Blaauw R., Moser D.E., Kingery A.: A catalogue of video records of the 2013 Chelyabinsk superbolide. Astronomy and Astrophysics 585, A90, 2016).

J. Borovička was invited by the editors of the book Asteroids IV to contribute with a chapter about meteorite falls (Borovička J., Spurný P., Brown P.: Small Near-Earth Asteroids as a Source of Meteorites In: Asteroids IV, Eds.: P. Michel, F.E. DeMeo, W.F. Bottke. The University of Arizona Press, pp. 257-280, 2015). Asteroids IV is the fourth one in a series of books about asteroids published nearly in a ten-year period and summarizing the achievements in the field during the last decade. The most important part of the chapter is the summary and the evaluation of the 22 instrumentally observed meteorite falls known at that time. The most interesting cases were discussed in the context of structure and origin of asteroids. Two of the three authors are members of our Team and they contributed together with more than 80% of the text as well as with three tables compiling the data about the instrumentally observed meteorite falls.

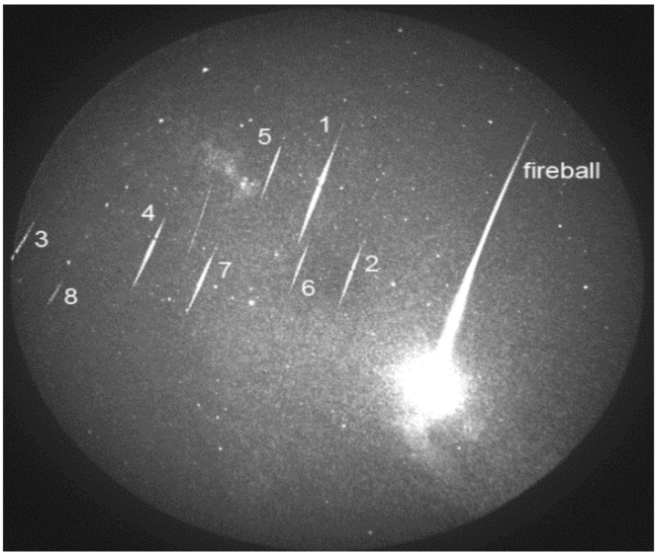

Fig. 4: The epsilon Perseid cluster

Finally, and most importantly, we significantly contributed to the book Meteoroids published by the Cambridge University Press. The book was a project of the IAU Commission F1 'Meteors, Meteorites, and Interplanetary Dust' led by G. Ryabova. The purpose of the book was to present the current status of knowledge and serve as the main reference in the field for the next 10 – 15 years. Members of our Team contributed with three of twelve chapters, two of them as leading authors:

Meteoroids: Sources of Meteors on Earth and Beyond, Eds.: G.O. Ryabova, D.J. Asher, M.D. Campbell-Brown, Cambridge University Press, Cambridge, UK (2019)

- Chapter 1: Popova O., Borovička J., Campbell-Brown M.D.: Modelling the entry of meteoroids. pp. 9-36
- Chapter 2: Borovička J., Macke R.J., Campbell-Brown M.D., Levasseur-Regourd A-C., Rietmeijer F.J.M., Kohout T.: Physical and chemical properties of meteoroids. pp. 37-62
- Chapter 4: Koten P., Rendtel J., Shrbený L., Gural P., Borovička J., Kozak, P.: Meteors and meteor showers as observed by optical techniques. pp. 90-115

Group Asteroids

Formation and evolution of asteroids by rotational fission

- Pravec P., Fatka P., Vokrouhlický D., Scheeres D.J., Kušnirák P., Hornoch K., Galád A., et al., Asteroid clusters similar to asteroid pairs. Icarus, 304, 110-126, 2018
- Pravec P., Fatka P., Vokrouhlický D., Scheirich P., Ďurech J., Scheeres D.J., Kušnirák P., Hornoch K., Galád A., Pray D.P., Krugly Yu.N., Burkhonov O., Ehgamberdiev Sh.A., Pollock J., Moskovitz N., Thirouin A., Ortiz J.L., Morales N., Husárik M., Inasaridze R.Ya., Oey J., Polishook D., Hanuš J., Kučáková H., et al., Asteroid pairs: A complex picture. Icarus, 333, 429-463, 2019

- Fatka P., Pravec P., Vokrouhlický D., Cascade disruptions in asteroid clusters. Icarus, 338, 113554 (11 pp), 2020
- Vokrouhlický D., Pravec P., Ďurech J., Bolin B., Jedicke R., Kušnirák P., Galád A., Hornoch K., et al., The young Datura asteroid family. Spins, shapes, and population estimate. Astronomy and Astrophysics 598, A91 (19pp), 2017
- Vokrouhlický D., Pravec P., Ďurech J., Hornoch K., Kušnirák P., Galád A., Vraštil J., Kučáková H., et al., Detailed Analysis of the Asteroid Pair (6070) Rheinland and (54827) 2001 NQ8. Astronomical Journal, 153:270 (17pp), 2017
- Vokrouhlický D., Ďurech J., Pravec P., Kušnirák P., Hornoch K., et al., The Schulhof family: Solving the age puzzle. Astronomical Journal, 151:56 (12 pp), 2016
- Žižka J., Galád A., Vokrouhlický D., Pravec P., Kušnirák P., Hornoch K., Asteroids 87887 – 415992: the youngest known asteroid pair? Astronomy and Astrophysics 595, A20 (11pp), 2016
- Ďurech J., Vokrouhlický D., Pravec P., Hanuš J., Farnocchia D., Krugly Yu.N., Ayvazian V.R., Fatka P., Chiorny V.G., Gaftonyuk N., Galád A., Groom R., Hornoch K., Inasaridze R.Y., Kučáková H., Kušnirák P., et al., YORP and Yarkovsky effects in asteroids (1685) Toro, (2100) Ra-Shalom, (3103) Eger, and (161989) Cacus. Astronomy and Astrophysics 609, A86 (10pp), 2018
- Moskovitz N.A., Fatka P., et al., A common origin for dynamically associated near-Earth asteroid pairs. Icarus 333 165–176, 2019

A predominant formation and evolution mechanism of small (km-sized and smaller) asteroids appears to be the process of rotational fission. The knowledge of the mechanism and its outcomes is important for understanding how small asteroids, both in the main belt and in the near-Earth space, were created and what their properties are. In the series of papers, we studied physical and dynamical properties of asteroids formed by this process and placed constraints to the rotational fission theory. Our studies ranged from constraining the thermal YORP effect, which appears to be a mechanism spinning up asteroids to their critical spin frequencies at which they fission, over determining properties of asteroid pairs, which are couples of asteroids orbiting on highly similar heliocentric orbits that escaped each other very recently, to studies of young asteroid clusters (mini-families) that appear to be largely formed by rotational fission as well.

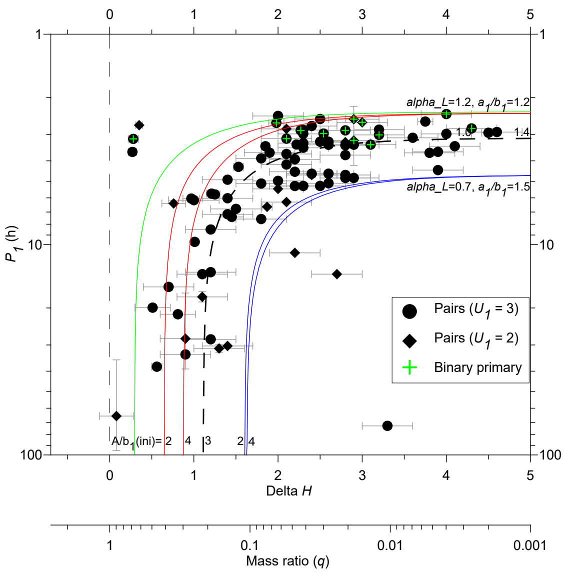

Fig. 5: Primary rotation periods vs mass ratios of asteroid pairs. More than 90% of asteroid pairs are within the upper and lower limits (green and blue curves) predicted by the theory of rotational fission. (Pravec et al., 2019).

We determined several key characteristics of the spin-fission pairs and systems, such as their ages (ranging from ~10^4 to a few 10^6 yr), sizes, spins and shapes. We found that while the basic theory of rotational fission explains most of the observed properties of the asteroid systems, there are certain features that indicate more complexity of the process, calling for developing a more advanced theory. Among them, the most interesting are the following: (1) The primaries of some asteroid pairs are actually binary systems (having satellites), so those pairs are actually systems with one escaped and one bound secondaries. (2) A few percent of asteroid pairs have high size ratios that were unpredicted by the basic theory, which indicates the presence of an additional source of energy. (3) Some asteroid clusters were formed by cascade disruptions, with two or more fission events over the past 10^6 yrs. Overall, we found that spin-fission asteroid systems are a complex population and its thorough understanding will require further detailed studies, which should give us a better knowledge of small asteroids, including potentially dangerous ones in the near-Earth space.

The Team has contributed to the publications in several key points. They identified/discovered many of the studied asteroid pairs and some of the asteroid clusters, obtained or organized photometric observations of the objects, determined their spin periods and sizes, determined or constrained their ages, interpreted (together with other co-authors) the obtained data and compared them to predictions from the rotation fission theory. Their contributions to the individual papers ranged from 10 to 80%.

Interstellar asteroid in an excited spin state

- Fraser W.C., Pravec P., Fitzsimmons A., Lacerda P., Bannister M.T., Snodgrass C., Smolić I., The tumbling rotational state of ‚Oumuamua. Nature Astronomy 2, 383-386, 2018.

The discovery of the first interstellar object ‘Oumuamua in October 2017 provided a unique opportunity to study a planetesimal born in another planetary system. We collected and analysed its photometric measurements that were taken with large telescopes in the world after its discovery from 25 to 30 October 2017. We found that the object is not in a basic spin state with minimum rotational energy, but it is in an excited spin state, showing two periods (rotation and precession).

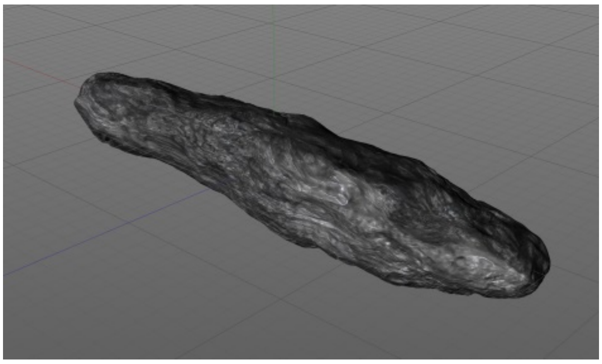

Fig. 6: Artist's impression of the interstellar asteroid ‘Oumuamua. (Courtesy ESO.)

While the origin of the state is unknown, it appears to be an original excitation from its creation in its mother star’s system or an outcome of the process of its ejection from the system. We also obtained a constraint on its extremely elongated (cigar-like) or flattened (pancake-like) shape, with a lower limit on the longest-to-shortest axis ratio of 5:1. This extreme shape suggests that the body has a rigid internal structure with non-zero cohesion. In addition, we found that the object exhibits a variable colour over its surface as it rotates, within a range that is broadly consistent with Solar System asteroids, such as the P- and D-type asteroids, Jupiter Trojans and dynamically excited Kuiper belt objects. These characteristics are unique and not seen in small Solar System bodies, making ‘Oumuamua an extremely interesting but puzzling object.

P. Pravec did the key analysis of the photometric data and found that the interstellar asteroid is in an excited spin state, and constrained its shape. He also contributed to the interpretation of the data in terms of damping timescale estimation. His contribution represented about 30% of the work on this publication.

Binary asteroids, their spin, shape and orbit properties

- Pravec P., Scheirich P., Kušnirák P., Hornoch K., Galád A., et al., Binary asteroid population. 3. Secondary rotations and elongations. Icarus, 267, 267-295, 2016
- Scheirich P., Pravec P., Jacobson S.A., Ďurech J., Kušnirák P., Hornoch K., et al., The binary near-Earth Asteroid (175706) 1996 FG3 — An observational constraint on its orbital evolution. Icarus, 245, 56-63, 2015
- Carry B., Matter A., Scheirich P., Pravec P., et al., The small binary asteroid (939) Isberga. Icarus, 248, 516-525, 2015
- Becker T.M., Howell E.S., Nolan M.C., Magri C., Pravec P., Taylor P.A., Oey J., Higgins D., Világi J., Kornoš L., Galád A., et al., Physical modelling of triple near-Earth Asteroid (153591) 2001 SN263 from radar and optical light curve observations. Icarus, 248, 499-515, 2015

Binary asteroids, i.e., systems of two bodies orbiting each other, are frequent among small (km-sized and smaller) asteroids in the main belt as well as in the near-Earth space. They are interesting both scientifically, as they reveal some key asteroid properties and formation mechanisms, as well as for planetary safety as diverting a dangerous binary asteroid would pose more challenge than single asteroids. In the four papers, we continued our long-term investigations of binary asteroids. We focused on describing rotation and shape properties of the secondaries of a sample of 46 binary asteroids, on constraining a long-term evolution of the so-far best described orbit of a binary near-Earth asteroid, on determining properties of the main-belt binary asteroid Isberga by combining photometric, spectroscopic and interferometry data, and on physical modelling of the unusual triple (i.e., having two satellites) near-Earth asteroid (153591) from combination of radar and photometric observations. We compared our data with theories of binary asteroid dynamics. In particular, we found that secondaries of close binary asteroid systems are in 1:1 spin orbit resonance, while those on more distant, wider orbits have asynchronous rotations, which agrees with predictions from the theories of binary asteroid dynamics, and we also found that their elongations are limited to axis ratios ≤ 1.5 which appears to be due to their dynamical or structural stability requirements. For the binary near-Earth asteroid (175706), we found that its mutual orbit did not evolve during the 17 years of our observations, suggesting that it is in a state of equilibrium between the thermal BYORP effect acting on the mutual orbit and tides between the binary system components. For the binary main-belt asteroid Isberga, we found that it is a typical representative of binary asteroids. For the triple asteroid (153591), we found that while the inner satellite is in the 1:1 synchronous rotation, the outer one is asynchronous, and we determined bulk densities of the three components of the triple asteroid that are consistent with its primitive material composition suggested by its B taxonomic type. Overall, these studies further advanced our knowledge of binary asteroids and they also suggested ways how we can obtain a more thorough understanding of them with further observations in the future.

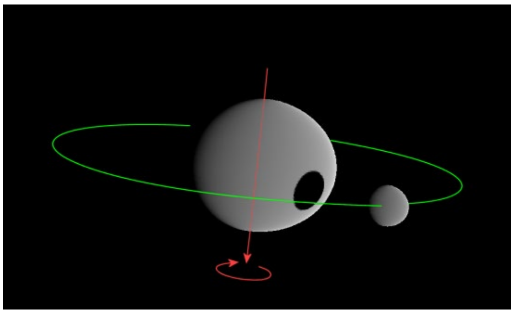

Fig. 7: A model of the binary near-Earth asteroid (175706) 1996 FG3 (Scheirich et al., 2015).

The Team has contributed to the publications in several key points. They discovered several new binary asteroids, obtained or organized photometric observations of the studied objects, determined their spins and estimated shapes, determined their mutual orbits, interpreted (together with other co-authors) the obtained data and compared them to the predictions from theories of binary asteroid dynamics. Their contributions to the individual papers ranged from 10 to 70%.

Support of the NASA DART and ESA Hera space missions to (65803) Didymos

- Michel P., Cheng A., Küppers M., Pravec P., Blum J., Delbo M., Green S.F., Rosenblatt P., Tsiganis K., Vincent J.B., Biele J., Ciarletti V., Hérique A., Ulamec S., Carnelli I., Galvez A., Benner L., Naidu S.P., Barnouin O.S., Richardson D.C., Rivkin A., Scheirich P., et al., Science case for the Asteroid Impact Mission (AIM): A component of the Asteroid Impact & Deflection Assessment (AIDA) mission. Advances in Space Research, 57, 2529–2547, 2016
- Cheng A.F., Michel P., Jutzi M., Rivkin A.S., Stickle A., Barnouin O., Ernst C., Atchison J., Pravec P., Richardson D.C., AIDA team, AIM team, Asteroid Impact & Deflection Assessment mission: Kinetic impactor. Planetary and Space Science, 121, 27–35, 2016
- Michel P., Kueppers M., Sierks H., Carnelli I., Cheng A.F., Mellab K., Granvik M., Kestilä A., Kohout T., Muinonen K., Näsilä A., Penttila A., Tikka T., Tortora P., Ciarletti V., Hérique A., Murdoch N., Asphaug E., Rivkin A., Barnouin P., Campo Bagatin A., Pravec P., Richardson D.C., Schwartz S.R., Tsiganis K., Ulamec S., Karatekin O., European component of the AIDA mission to a binary asteroid: Characterization and interpretation of the impact of the DART mission. Advances in Space Research, 62, 2261-2272, 2018
- Cheng A.F., Rivkin A.S., Michel P., Atchison J., Barnouin O., Benner L., Chabot N.L., Ernst C., Fahnestock E.G., Kueppers M., Pravec P., et al., AIDA DART asteroid deflection test: Planetary defense and science objectives. Planetary and Space Science, 157, 104-115, 2018
- Hirabayashi M., Davis A.B., Fahnestock E.G., Richardson D.C., Michel P., Cheng A.F., Rivkin A.S., Scheeres D.J., Chesley S.R., Yu Y., Naidu S.P., Schwartz S.R., Benner L.A.M., Pravec P., et al., Assessing possible mutual orbit period change by shape deformation of Didymos after a kinetic impact in the NASA-led Double Asteroid Redirection Test. Advances in Space Research, 63, 2515-2534, 2019

The NASA DART (Double Asteroid Redirection Test) and the ESA Hera missions to the binary asteroid (65803) Didymos, which we discovered with photometric and radar observations (Pravec et al., IAU Circular 8244, 2003), are the key space missions in the field of planetary safety against asteroid impacts. The DART will be the first space experiment to demonstrate the asteroid impact hazard mitigation by using a kinetic impactor to deflect an asteroid in 2022, and the Hera will provide a detailed characterization of outcomes of the experiment during its stay around the binary asteroid a few years later. In these papers, we described the proposed missions, their rationales and expected outcomes, and we also gave basic data on their target, the binary asteroid Didymos. We also outlined the important role of further detailed ground-based observations of Didymos in the years before as well as after the DART impact (which will happen in September-October 2022) that are necessary for both the preparation of the missions and for the determination of outcomes of the deflection experiment.

P. Pravec and P. Scheirich (in Michel et al. 2016) contributed with analyses of ground-based photometric data obtained for the binary asteroid Didymos for the preparation of the space missions and with the planning of further observations that are necessary for ensuring the success of the missions. Their contributions to the papers were about 5 to 10%. P. Pravec became a member of the DART Investigation Team, a co-chair of the Hera Working Group 2 on Remote Observations, and a Data Analysis Coordinator of the joint DART-Hera Remote Observations Working Group.

Research activity and characterisation of the main scientific results

In the evaluated period, we mainly worked on the following research topics:

Galaxy formation and evolution
One of the key challenges in the galaxy evolution theory is to understand the star formation history of galaxies - in particular, how the star formation is triggered and how it can be suddenly quenched. The environmental effects in galaxy clusters and groups are thought to play an important role, especially the ram pressure stripping (RPS) of the interstellar medium as galaxies move through the surrounding intra-cluster medium. Other mechanisms include gravitational interactions between galaxies and the tidal influence of the cluster potential.

In recent years numerous cluster galaxies with jellyfish-like 'tails' of stripped gas have been discovered. These are multiphase, observed in HI, Hα and X-rays, many containing young stars. RPS thus not only quenches the star formation in galaxies, but can initiate a new star formation in the striped gas. Jáchym et al. (2017, ApJ, 839, 114) showed for the first time that tails of jellyfish galaxies may be dominated by cold molecular components. In the Coma galaxy D100, IRAM 30m observations revealed large amounts of molecular gas that exceed the mass of ionized hot and warm phases together. The molecular-to-ionized gas mass ratio is elevated due to the excitation and the heating from the shocks induced by the ram pressure. HST imaging of the D100 galaxy (Cramer et al. 2019, ApJ, 870, 63) discovered blue sources coincident with the Hα tail, which were identified as young stars formed in the tail, however, the star formation rate in the tail is a factor of 10 lower than the total Hα flux of the tail would suggest. With ALMA, the first high-resolution map of the cold molecular gas distribution in a jellyfish galaxy was obtained (Jáchym et al. 2019, ApJ, 883, 145). In the prototypical RPS galaxy ESO137-001, mostly larger CO features were found, with virial parameters that indicate they are not gravitationally bound and will disperse with time. The ALMA observations also displayed CO filaments oriented in the direction of the tail that are likely young molecular features formed in situ.

Besides gas clouds clearly connected with cluster galaxies, there are others, more mysterious ones: certain HI clouds in Virgo are isolated, optically dark, and with high velocity widths suggestive of rotation. We explored a variety of possible origins for the dark neutral gas structures. Köppen et al. (2018, MNRAS, 479, 4367) describe how to analytically calculate the effects of ram pressure stripping. In Minchin et al. (2019, AJ, 158, 121) we used this technique to assess the progenitor candidate galaxies of the ALFALFA complex 7 cloud, finding that none can fully explain the unusual features of this large, massive structure that is well-detached from its parent galaxy. However, in Taylor et al. (2020, AJ, in press) we demonstrated that ram pressure is the most likely mechanism to explain a population of short gas tails we discovered elsewhere in the Virgo cluster. The research into smaller, detached clouds is ongoing. In Taylor et al. (2016, MNRAS, 461, 3001) we showed that harassment has difficulties in producing features with the similar isolation and velocity widths (a conclusion strongly reinforced in Taylor et al. 2017, MNRAS, 467, 3648), while if the clouds are gravitationally bound by dark matter - essentially galaxies in their own right - then they could survive the tidal effects of the cluster for several gigayears. We are now beginning to incorporate the effects of the intra-cluster medium and ram pressure stripping into these simulations to see how this will affect our conclusions.

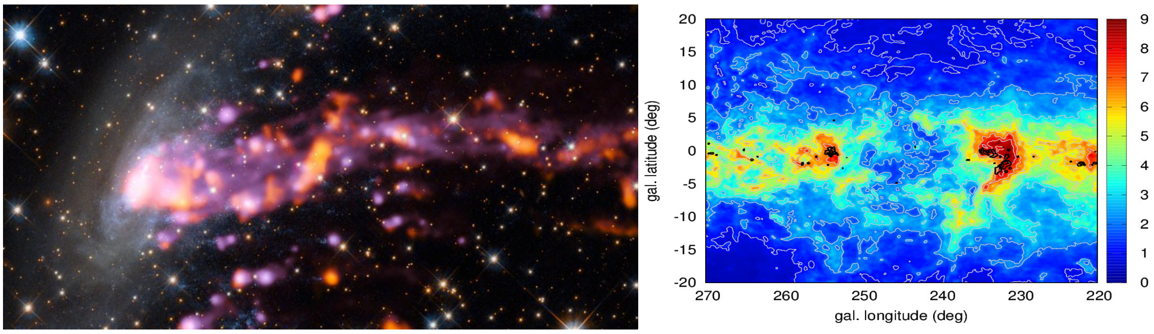

Fig. 1: Left: Multiwavelength study of galaxy ESO137-001; combination of mm radio (ALMA), Hα (VLT/MUSE) and optical (HST). Right: One of the largest supershells in the Milky Way - GS242-03+37 - extends through the whole thickness of the Galactic disc. Young star forming regions are found in its walls. Observation taken in 21cm neutral hydrogen line (Credit: HI4PI survey).

Structures in the interstellar medium

HI shells and supershells belong to the most striking structures in the distribution of the interstellar medium in galaxies. The majority of them are created by energetic activities of massive stars, mostly by supernovae explosions combined with the intense radiation and stellar winds, but there are structures of unknown origins, where the stellar origin is not probable. The role of HI shells is not straightforward: walls of these structures expand into the neighbouring interstellar medium destroying existing molecular clouds and therefore decreasing the star formation in their vicinity, but also sweeping the surrounding material into dense sheets, promoting the creation of new clumps and clouds and thus increasing the star formation. We study expanding shells both observationally and theoretically in the following papers.

Ehlerová & Palouš (2016, A&A 587, 5) created a catalogue of HI shells in the outer Milky Way and explored the correlation between HI shell walls and the presence of molecular clouds observed in CO line. Zychová & Ehlerová (2016, A&A 595, 49) analysed a system of two colliding interstellar bubbles. Mostly theoretical work of Dinnbier et al. (2017, MNRAS 466, 4423), that studies the gravitational fragmentation of shells, discovers a new type of instability and explores its impact on the star formation in shell walls. Ehlerová & Palouš (2018, A&A 619, 101) analysed in detail one of the largest supershells in our Galaxy (GS242-03+37, see Fig. 1) and by that studied the effect of large shells on their surroundings.

Massive star clusters

Young massive star clusters are rare: there are only about ten young star clusters more massive than 10^4 Solar masses in our Galaxy, and clusters with masses higher than 10^5 Solar masses have been only found in external galaxies. However, they were much more common in the early Universe, at the peak of the cosmic star formation rate, when a significant fraction of all existing stars was formed. Understanding how the star formation proceeded at that time, whether it was qualitatively different than nowadays, is interesting by itself, however, it also impacts other fields, e.g. cosmology, the formation of galaxies and the origin of chemical elements in the Universe. Among many open questions, a particularly interesting one is how the globular clusters were formed. It was found that globular clusters (very old massive star clusters found typically in galactic halos) consist of several populations of stars which differ in their chemical composition. Moreover, spectroscopy of red giants in globular clusters revealed very unusual chemical patterns that are not observed in any other known objects.

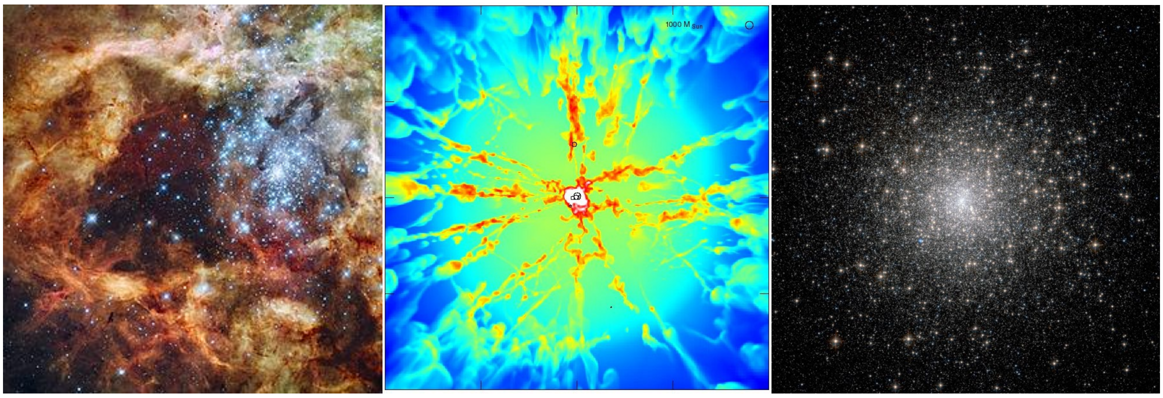

Fig. 2: Left: R136 in the Large Magellanic Cloud (the most massive young star cluster in the Local group). Credit: NASA, ESA (HST). Middle: RHD simulation with a secondary star formation in a young massive cluster (Wünsch et al., 2017). Right: Galactic globular cluster M15. Credit: NASA, ESA (HST).

We develop, in collaboration with INAOE in Puebla (Mexico), a model of *rapidly cooling shocked stellar winds* that aims to address the question of the origin of multiple stellar populations in globular clusters. The model and its implementation using the radiation-hydrodynamic code is described in Wünsch et al. (2017, ApJ 835, 60). Additional aspects of this model (e.g. the theory of self-shielding of dense clumps) are described in Palouš et al. (2017, IAUS316, 251) and Wünsch et al. (2017, IAUS316, 294). The impact of supernovae on the secondary star formation and on the formation and destruction of dust by them is studied in a series Martínez González et al. (2017, ApJ 843, 95; 2018, ApJ 866, 40; 2019, ApJ 887, 198). In Tenorio Tagle et al. (2019, ApJ 879, 58) we explore the relation between the star formation efficiency and the properties of multiple stellar populations in globular clusters. Further, we describe an alternative model of the formation of multiple stellar populations in the shell created by the exploding Population III star in Recchi et al. (2017, Ap&SS 362, 183).

Green pea galaxies

Green pea galaxies are highly star forming compact dwarf galaxies typically observed at medium redshifts z=0.2-0.3, with a relatively high fraction of leaking ionising radiation. They are thought to be equivalents of high-redshift starburst galaxies that may be responsible for the re-ionisation of the Universe. In Izotov, Orlitová et al. (2016, Nature 529, 178) we report the detection of a significant Lyman continuum escape, and demonstrate the conditions under which the ionizing radiation can leak. In Orlitová et al. (2018, A&A 616, A60) we report the discovery of peculiar double-peaked Lyman alpha line profiles at Green pea galaxies that are difficult to be reproduced by models. In collaboration with the Relativistic astrophysics group (J. Svoboda) we study the properties of the X-ray radiation of three Green pea galaxies by observing them with the XMM-Newton Space Observatory.

Gould's Belt

Gould's Belt is a system of young stars within 1 kpc from the Sun. The origin and evolution of the young stars is explored with the astrometric data provided by GAIA astrometric satellite. Currently we use the DR2 data release, in the future we shall use coming DR3 and DR4. The main question is the origin of nearby OB associations, how they are connected to nearby molecular clouds, and how their recent formation is connected to the structure of the Milky Way. This research is performed in collaboration with C. Ron of the Planetary Systems Group. A review paper Palouš & Ehlerová, “Gould's Belt: Local Large-Scale Structure in the Milky Way” was published in the Handbook of Supernovae (ISBN 978-3-319-21845-8, Springer International Publishing AG, 2017 p. 2301). Recently we published a paper Palouš, Ehlerová & Ron, 2019, "Gould's Belt: As Seen in Gaia DR2” (2019, ASPC, 519, 169).

Modelling X-ray spectral, timing and polarisation properties of AGN and XRBs
The X-ray spectral, timing and polarisation properties of the radiation coming from the close vicinity of black holes in AGN and XRBs enable us to probe the effects of strong gravity, to learn about the black-hole properties, its mass and spin, and to study accretion processes. We investigate the properties of thermal radiation emitted by the accretion disc, Comptonization of this radiation in the hot corona above, that is responsible for the primary X-ray radiation, as well as the re-processing of the primary X-rays that fall back onto the accretion disc. These on one hand increase the disc temperature and on the other hand produce the disc-reflection spectrum with its distinct features as the soft excess (in 0.3-1 keV), the fluorescent iron K alpha spectral line (around 6.4 keV) and the Comptonized hump (above 10 keV).

We develop numerical codes that can be used to model different components of these systems - a black hole, an accretion disc and the corona (or hot inner accretion flow) and study their properties in spectral, timing and polarisation domains. We created a library for computing the photon trajectories in the curved space-time of a black hole with arbitrary mass and spin, SIM5 (Astrophysics Source Code Library, record ascl:1811.011). We developed a package of numerical codes, KY, to model the accretion disc emission, i.e. both the thermal disc radiation as well as the re-processed reflection spectra from black-hole accretion discs (e.g. Dovčiak & Done 2016, AN, 337, 441; Kammoun et al. 2019, MNRAS 485, 239). Further we developed new codes to model the X-ray and UV/optical (thermal) reverberation, KYNREVERB (e.g. Caballero-Garcia et al. 2018, MNRAS, 480, 2650; Kammoun et al. 2019, ApJL, 879, L24). Both of these numerical packages can be used within the XSPEC, a widely used platform for fitting X-ray observational data. To model the primary X-ray radiation and properties of the corona, we developed a brand-new numerical code, MONK (Zhang et al. 2019). In the future we want to use this code to produce XSPEC table models to fit the spectral, timing and polarisation properties of the corona. After extensive tests and the use with data, we provide our codes and tables to the astrophysical community at our Institute projects web page (see e.g. https://projects.asu.cas.cz/stronggravity/kyn).

Polarization in AGN, XRBs and Sgr A*
Recently, the X-ray polarisation astronomy got a new incentive as new X-ray missions with a polarimeter on-board have been approved - the NASA’s IXPE mission to be launched in 2021 and the Chinese eXTP mission with an expected launch in 2027. Members of our Team joined these efforts in multiple ways - by our research contribution to their scientific programme, by co-organizing the mission preparations as collaborators, one of us participating in a scientific consortium structure as the science topical working group Chair (in the IXPE mission), and by arranging a hardware contribution by the Czech Republic, thus becoming a member of a hardware consortium (in the eXTP mission).

We used our models to predict the polarisation for different systems emitting X-ray radiation – we computed time variations of the polarization signal from AGN due to cloud obscuration (Marin & Dovčiak, 2015, A&A, 573, A60), the polarization of reflection nebulae in the Galactic centre (Marin et al., 2015, A&A, 576, A19), polarized scattered fluxes by the exoplanet HD 189733b (Marin & Grosso, 2017, ApJ, 835, 283), the contribution of parsec-scale material to the polarized X-ray spectrum of type 1 Seyfert galaxies (Marin et al., 2018, MNRAS, 478, 950) and we predicted the X-ray polarization of type 2 Seyfert galaxies (Marin et al. 2018, MNRAS, 473, 1286). We also modelled the optical and the UV polarization of AGNs originating in either uniform-density or clumpy regions (Marin et al., 2015, A&A, 577, A66).

AGN spectral states

We study similarities of accretion processes between black holes of largely different mass, stellar-mass black holes in X-ray binaries and supermassive black holes in galactic nuclei. While stellar-mass X-ray binaries are known to change their accretion properties within several weeks to months, the supermassive black holes are much larger and thus less variable. There are, however, similarities between these two distinct classes of black holes, such as the presence of an accretion disc and also the presence of a relativistic highly-collimated outflow, the so-called jet, in some sources.

In our recently published paper (Svoboda et al., 2017, A&A, 603, A127), we performed the largest study of AGN spectral states using the entire archive of X-ray *and* optical/UV sources detected by XMM-Newton in its first ~15 years of operations to address one of the fundamental problems in modern astrophysics: Does the accretion onto black holes scale solely, or primarily with mass? This unprecedented parent sample allowed us to extract the largest and best-quality sample for this kind of studies with a population of ~1,500 galaxies hosting an accreting super-massive black hole with high-quality simultaneous optical and X-ray data. We mapped the spectral hardness (ratio of the X-ray to the total luminosity) and the luminosity of the largest existing sample of accreting black holes with simultaneous optical and X-ray observations. Our study provides an observational support to the hypothesis that accretion onto super-massive black hole works in a similar way as the stellar-mass black holes in X-ray binaries, and that XRB and AGN follow similar evolutionary paths.

Since 2019, there has been a junior team led by J. Svoboda to address the AGN spectral states in more detail. Namely, we will focus on AGN with known radio morphology from sensitive radio observations to see whether the jet launching mechanism is closely related to the accretion state and evolves similarly as for X-ray binaries. There is an observational evidence that the jets in stellar-mass black holes are quenched once they move to the so-called soft state. If the jet presence in AGN appeared to be related to the accretion state and AGN state evolution is similar to XRBs, this would provide a natural explanation for the observed radio dichotomy of AGN. Further, the team aims to develop a robust method to decompose the AGN emission from host-galaxy contamination in the optical to UV domain to have precise measurements of the thermal radiative output from the accretion discs that are not as hot in AGN as in XRBs.

Quasi-periodic oscillations

Accreting black holes in binary systems often exhibit quasi-periodic oscillations (QPOs) of the observed X-rays. Sometimes the frequency of these oscillations is very high (in kilohertz range) and they occur at two distinct peaks. QPO properties differ between sources, however, it appears that they keep a fixed frequency ratio of small rational numbers. The exact origin of this phenomenon is still not very clear. High frequencies of QPOs roughly correspond to orbital frequencies of the matter in close vicinity of the central black hole, moreover, they roughly inversely scale with its mass what likely suggests a relativistic origin of this phenomenon. In addition, a nearly harmonic sequence of the frequencies suggests they correspond to some distinct modes of the underlying accretion structure with possibly non-linear effects such as resonance involved. A precise modelling of these oscillations would provide an independent and very useful probe into a strong gravitational field of the compact objects and help to measure some of their crucial parameters, such as black-hole spin.

Our group is involved in examining the stability and oscillation properties of the accretion flows under various conditions. We explore both thick and thin accretion flows and various excitation mechanisms of their oscillations. In the past five years, we studied the excitation/damping of trapped acoustic waves in thin accretion disks (so called p-modes) due to turbulent viscosity and corotation resonance in collaboration with the astrophysical group at Cornell University in the USA (see e.g. Miranda et al. 2015, MNRAS 446, 240). In collaboration with the Institute of Physics at Silesian University in Opava (IP SU), we developed a finite-element code to explore possible modes of thick accretion disks (tori) with constant angular momentum distributions. This represents a complementary case to thin accretion disks with nearly Keplerian angular momentum distributions. Currently, we work on an extension of the code to include fully general angular-momentum distributions to adopt a variety of other types of accretion flows and their geometries.

Strong high-frequency QPOs are also observed in accreting low-mass X-ray binaries, where the accretors are neutron stars. In this case, QPO frequencies vary in time, but follow tight correlation between each other. In collaboration with IP SU, we developed a model based on oscillation modes of thick accretion tori that describes this correlation remarkably well (see Török et al., 2016 ApJ, 833, 273).

MHD simulations of wind in High-mass X-ray binary systems

High-mass X-ray binary systems (HMXBs) are interacting binaries in which a compact companion, either a neutron star or a black hole, orbits a massive early-type star, typically an OB supergiant. This type of stars is characterized by an enhanced mass-loss rate of the order of $\sim 10^{-6}$ Solar masses per year. The compact companion is immersed in the stellar wind and accretes material from it, giving rise to a strong X-ray flux. The wind of the massive star is severely disrupted by the gravity and photo-ionization of the companion and its accretion flow. We developed a code for three-dimensional time-dependent radiation hydrodynamic simulations of stellar winds in interacting binaries to improve models of high-mass X-ray binaries and to explore the properties of circumstellar matter. We used this code to interpret the X-ray state transitions of Cygnus X-1 (Čechura & Hadrava, 2015, A&A 575, A5). We also developed a new method of interpreting Doppler tomograms of observed XRB spectra that is based on a comparison with synthetic Dopplerograms calculated from radiation-hydrodynamic models of the circumstellar matter in the binary system. We applied this method to the optical spectra of Cyg X-1 obtained mainly by the Perek 2m Telescope of the Astronomical Institute in Ondřejov (Čechura et al., 2015, MNRAS 450, 2410). We found that our model with the assumed parameters fits well the observations in both high/soft and low/hard states of the object.

Magnetic fields around black holes

The electromagnetic field is governed by Maxwell's equations. These are the first-order differential equations for the electric and magnetic intensity vectors. When expressed in the equivalent, and perhaps more elegant tensorial formalism, the mutually coupled equations for the field intensities can be unified in terms of the electromagnetic field tensor, comprising both the electric and the magnetic field components in a single quantity. In the astrophysical context, coupling with plasma is essential. In the context of black holes, effects of strong gravity also have to be taken into account. Near rotating compact objects, neutron stars and black holes, the field lines are wildly deformed by rapidly moving plasma and strong gravitational fields. Studying the effects of strong gravity is a traditional direction with interesting results achieved also in a broader collaboration with our colleagues at universities within the frame of Albert Einstein Centre in Prague. We address questions whether rotating black holes power relativistic jets? How the particles are accelerated near the event horizon? Is the motion regular or chaotic? Compelling answers may be beyond our reach yet for some time. However, the group of Karas, Kopáček, Suková, Araudo et al. has contributed to the field by publishing a series of related papers (ApJ, MNRAS, A&A, CQG, etc.) over the evaluation period. The adopted approach turns out to be particularly useful in the framework of the theory of relativity.

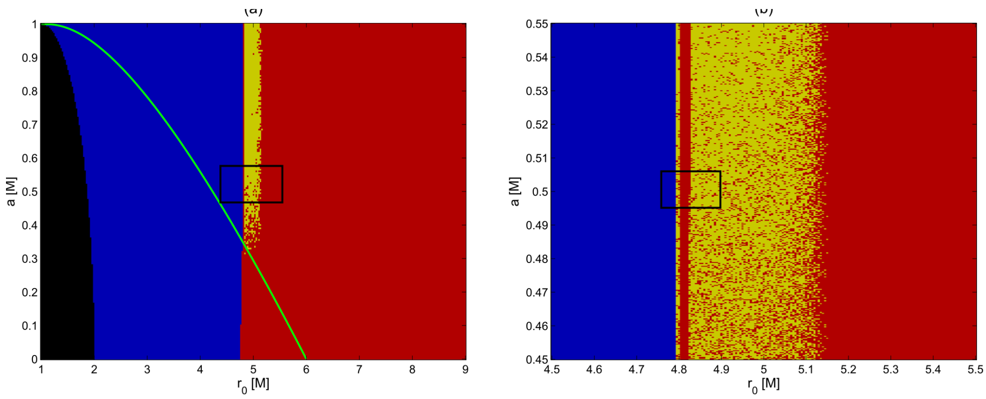

Fig. 3: Magnetic fields extract rotational energy from the black hole back and convert it to the outflowing Poynting flux and to kinetic energy of accelerated plasma flows. Such outflows are indeed observed, but the regions where they originate remain below resolution capabilities of present-day techniques. In our recent work we proposed that the conditions in the ergosphere can lead to a magnetic reconnection and chaotic motion occurring in the strong gravitational field of a rotating black hole (figure from Kopáček & Karas, 2018, ApJ, 853, 53).

Gravitational wave modelling

In 2017 a junior team led by G. Loukes-Gerakopoulos started a new direction of research by modelling sources of gravitational waves and computing the respective waveforms. In particular, we focus on Extreme Mass Ratio Inspirals (EMRIs), which are binary systems consisting of a primary super-massive black hole (SMBH) and a secondary stellar-mass compact object. In these binaries, the comparably lighter compact object can be viewed as moving in the gravitational field of the primary, where it slowly spirals towards the central black hole. The degradation of the orbit is caused by the loss of energy and angular momentum due to the gravitational radiation reaction. Such processes are predicted to routinely occur in the centres of galaxies, where the compact objects enter inspirals around the heavy central black holes due to complicated many-body dynamics of the surrounding dense stellar clusters.

Gravitational waves from EMRIs are promising sources for the space-based gravitational-wave detector LISA (Laser Interferometer Space Antenna). LISA is the L3 mission of ESA in its Cosmic Vision science programme currently scheduled for launch in the early 2030s. The EMRI signals detected by LISA will allow us to map the spacetimes around SMBHs. In return, this will also allow us to test whether the gravitational fields of SMBHs are well described by Einstein's General Relativity or not. The current consensus is that gravitational waveform template banks are necessary in order to be able both to detect and interpret the received signal.

In the source modelling we concentrate mainly on the inclusion of astrophysical effects modifying the simplest EMRI models, namely effects due to the finite size of the secondary objects or external gravitational perturbations. In both cases, we employ tools traditionally developed in the fields of dynamical astronomy and non-linear dynamics ranging from Poincaré sections to the canonical perturbation theory. For calculating the GW fluxes and the waveforms we use a time domain Teukolsky solver called Teukode developed by our collaborators at the University of Jena, and tools from the Black Hole Perturbation Toolkit.

Multiphase environment of Centaurus A
We studied the combined high-resolution ALMA and Chandra images of the central 500 pc of the Centaurus A galaxy. Our aim was to study the multi-phase gas distribution in the close vicinity of the central supermassive black hole. We perform CLOUDY simulations of the photoionized gas and dust illuminated by the broad-band Centaurus A continuum to examine what physical processes are responsible for multi-phase gas equilibrium. We conclude that the hot X-ray emitting plasma cannot coexist with the dusty gas at temperatures of 100 K in pressure equilibrium. The natural consequence of this result is that the cold CO emitting gas has to be shielded from the X-ray emission. We build a 3-D model and by projection we calculate the emissivity maps and match them to the observed images of the source. This study helps to determine the 3-D spatial distribution of the circumnuclear gas under the conditions of thermal equilibrium.
This work is currently being completed, where Abhijeet Borkar, Peter Boorman and Vladimir Karas are involved, in collaboration with colleagues from the Nicolaus Copernicus Astronomical Centre Polish Academy of Sciences, Centre for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland, Inter University Centre for Astronomy and Astrophysics, Pune, India, and Instituto di Radioastronomia, Instituto Nazionale di AstroFisica, Bologna, Italy. The Relativistic Astrophysics group is involved with performing the data reduction of the ALMA observations, the analysis of the submillimetre data with ALMA and the X-ray data with Chandra and NuSTAR, and the data interpretation.

Satellite geodesy and gravity field

Geo-applications of high-resolution gravity field models – a new method to detect and study causative underground bodies of various origin (trenches, volcanoes, lakes, river valleys, paleolakes, impact craters, etc) according to their fine density variations was implemented, the results published in a series of impacted papers (see below). We published a monograph with Springer: Gravitational Atlas of Antarctica (Klokočník et al., 2017, Arab. J. Geosci, 10, 199). The gravity aspects (gravity anomalies, the Marussi tensor of the second derivatives, gravity invariants, strike angles and virtual deformations) were computed and plotted for Antarctica. These gravity aspects (descriptors), which are derived from the top quality global static comprehensive high-resolution gravity field models, provide much more complete but complex information about the density variations beneath the Earth surface or ice than only the traditional gravity anomalies.

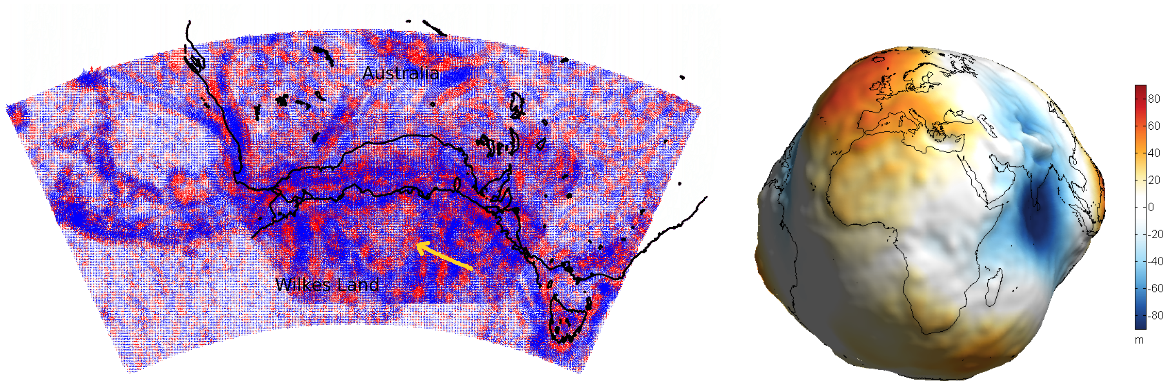

Fig. 4: Left: The virtual deformations showing internal tensions (blue compression, red dilatation) derived from the gravity field model EIGEN 6C4 for Wilkes Land, East Antarctica, showing a huge impact crater – originally Antarctica and Australia were connected (Klokočník et al., 2018, Planets and Space, 70, 135). Right: Geoid heights derived from the gravity field (Bezděk & Sebera, 2013, Comp. Geosci., 56, 127).

At least 2 candidates for subglacial volcanoes, 3 for subglacial lakes and 1 for a lake basin near the Lake Vostok in East Antarctica were discovered (Klokočník et al., 2016, Ann. Geophys., 59, 5). Our analyses independently supported the opinion that Wilkes Land in East Antarctica contains a huge impact crater (a crater basin with a mascon like on the Moon) which affected geological past of the Earth (~250 mil. years ago) similarly as the proven impact crater Chicxulub on Yucatan (~65 mil. years old) (Klokočník et al., 2018, Polar Sci, 17, 59). We also studied (with the gravity aspects) paleolakes on Sahara and confirmed their existence known or discovered / suggested before wholly independently by geologists. We add the discovery of one such paleolake along the Egyptian-Libyan border, under deep layers of sand. This land was still habitable 5000 - 7000 years ago. Now only few oases remain. We correlated the gravity signal with the possible position and the shape of two other paleolakes and/or the river system in Egypt (Klokočník et al., 2017, Arab. J. Geosci, 10, 199). The hypothetical impact structure in the Saginaw Bay (MI, USA) was tested as well (Klokočník et al., 2019, JGLR, 45, 12).

Time-variable gravity field from satellite GPS orbits. We continued the development and implementation of our original inversion method of the precise GPS orbital data into time-variable gravity fields (so-called monthly gravity solutions). Within the framework of recent Earth missions dedicated to observe the time-varying gravity (CHAMP, GRACE, GRACE-FO, GOCE, Swarm), a special attention is paid to the processing of non-gravitational forces measured by on-board accelerometers. We contributed to this topic especially within the ESA Swarm mission (Bezděk et al., Adv. Space Res. 2017, 59, 2512; ditto 2018, 62, 317). We also studied other small, but nowadays important perturbative accelerations, those due to the general theory of relativity (Bezděk and Letko, 2019, JAG, 161, 270) and due to ocean tides (Štěpánek et al., 2016, AGG, 13, 27). Finally, based on our long-term expertise and good results in this research area (Bezděk et al., 2016, GJI, 205, 1665; da Encarnacao et al., 2016, Planets & Space, 68, 127), our work group was invited to be one of the five international academic members of an ESA-organized consortium named “Multi-approach gravity field models from Swarm GPS data. The consortium started its work in 2017, currently it is foreseen to support its work in supplying the Swarm gravity fields until 2021 (http://jgte.github.io/gswarm). Related to our active role in the Swarm scientific community, in September 2019 our group was the main organizer of the 9th ESA Swarm Data Quality Workshop (details given below). For the gravity fields, we developed original routines for the spheroidal harmonic representations that were used 1) to update a high-resolution gravity model EGM2008 over the oceans where new data come from satellite altimetry every year (Sebera et al., 2016, Icarus, 272, 70), and 2) to model the gravity field of small bodies – the OSIRIS-REx target Bennu with the oblate harmonics, and Castalia with the prolate spheroidal harmonics. Our group also started new topics related to geomagnetism, for which we derived a global magnetic susceptibility map for geologic/tectonic interpretations based on satellite-only data (Sebera et al., 2019, Surv. Geophys., 40, 1229).

Global geodynamics, Earth rotation and galactic aberration

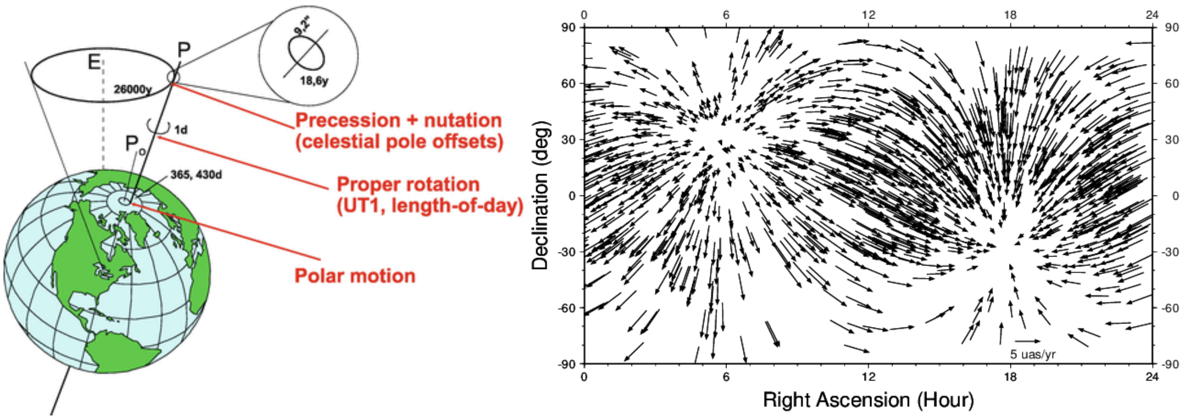

Fig. 5: Left: Earth rotation is described by Earth orientation parameters (Vondrák, 2018, IAG Symp., 147, 203). Right: Aberration proper motion field of extragalactic sources for an aberration constant of 5.8 μas/yr (McMillan et al., 2019, A&A, 630, A93).

The Prague part of the group continued studying **the effects of the geophysical fluids** (atmosphere, ocean, continental hydrology) and **geomagnetism on the Earth rotation**. It consists in studying movements of the Earth's spin axis in space (nutation) and in the Earth's body (polar motion). These motions were modelled using the integration of Liouville equations in Brzezinski's broad-band form. Newly we added an impulse-like excitation due to the geomagnetic jerks, the sudden changes of geomagnetic field, with the common use of excitations by atmosphere and ocean. It was demonstrated that the inclusion of excitation by geomagnetic jerks, in addition to atmospheric and oceanic excitation, improves the agreement between integrated and observed Earth orientation parameters substantially (Vondrák & Ron, 2015, Serb. AJ, 191, 59). Based on these results a new method for determining periods and quality factors of the eigenmodes of free core nutation (Vondrák & Ron, 2017, A&A, 604, A56) and of Chandler wobble in polar motion (Vondrák et al., 2017, Adv. Space Res., 59, 1395), free from the geophysical effects, was proposed.

Galactic aberration. An alternative method to detect the secular aberration drift induced by the solar system acceleration due to the attraction to the Galaxy centre was proposed by Titov&Krásná (2018, A&A, 610, A36). This method is free of the individual radio source proper motion caused by intrinsic structure variation. They developed a procedure to estimate the scale factor directly from a very long baseline interferometry (VLBI) data analysis in a source-wise mode within a global solution. This approach splits the systematic dipole effect and uncorrelated motions on the level of observational parameters. H. Krásná as a member of the IVS (VLBI Service for geodesy & astrometry) working group on Galactic aberration (WG8) further contributed to the Galactic aberration research as published in MacMillan et al. (2019, A&A, 630, A93). The findings of the WG8 were used by the IAU ICRF3 working group in the generation of the 3rd realization of the International Celestial Reference Frame (ICRF3).

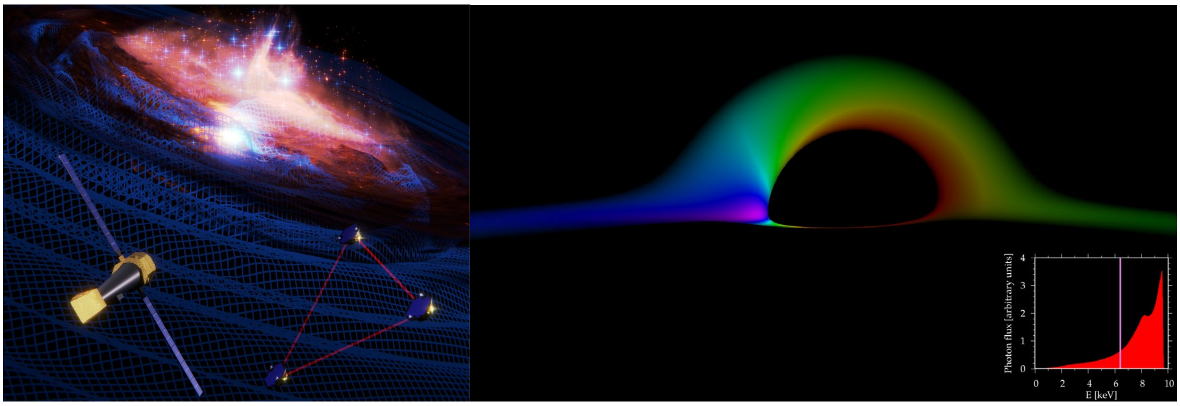

Fig. 6: Left: The large ESA missions ATHENA and LISA will reveal secrets of the Energetic and Gravitational Universe. The goal of the Strategy AV21 - Space for Mankind is a successful Czech involvement in these large European space projects. Right: Simulations of the frequency shift of radiation coming from a deep gravitational field of the closest neighbourhood of a black hole and corresponding spectral line profile in an offset (Credit: M. Dovčiak, ASU).

Strategy AV21 - Space for Mankind

The research programme Space for Mankind of the Strategy AV 21 aims to strengthen the cooperation between the scientific community and the technical teams in the development and the testing of new technologies for space research. There are three research teams in the Galaxies and Planetary System department:

- Hot and Energetic Universe - beyond the possibilities of ground-based laboratories
- Earth observation
- Gravitational Universe

The Hot and Energetic Universe group is involved in a large mission of the European Space Agency (ESA) ATHENA (Advanced Telescope for High Energy Astronomy). The ASU Team participates in the Athena Science Advisory Team. Michal Dovčiak is a co-chair of the working group Closest environments around supermassive black holes. In 2019, the Team also joined the instrumentation consortium of the main ATHENA scientific instrument X-IFU (X-ray Integral Field Unit). Jiří Svoboda became a member of the X-IFU Science Advisory Team and leads the Czech instrumentation team in collaboration with the Institute of Atmospheric Physics. The Czech contribution to the X-IFU detector will be the Remote Terminal Unit, an important electronic component to control the temperature in the central part of the detector and commanding other electronic and mechanical units. The team is also involved in the X-ray Chinese-European space mission eXTP (enhanced X-ray Timing and Polarimetry). The Czech team led by ASU will develop Collimator and Detector Frames for the innovative scientific instrument LAD (Large Area Detector).

The Earth Observation team is devoted mainly to two space missions, GRACE and Swarm and conducted related activities focused on the remote sensing of the Earth. They organized ESA Swarm Data Quality Workshop and Copernicus workshop to learn from the experts how to use the data collected from these missions. The Gravitational Universe team is involved in the consortium of the LISA (Laser Interferometer Space Antenna) mission, which is the space-based gravitational-wave observatory planned by ESA. The ultimate goal of this group is to get involved in the scientific simulations as well as to agree on providing a hardware contribution to the spacecraft.

All three teams are involved in several public outreach activities (exhibition Ad Infinitum at the Czech Academy of Sciences (CAS), exhibitions at several science festivals including the production of a 1:4 model of the ATHENA satellite or an artistic model of a black hole or a gravitational wave simulator).

Czech node of the European ALMA Regional Centre – Large Research Infrastructure

ASU hosts one of the nodes of the European ALMA Regional Centre network, the Czech ALMA node. Since 2016 the node has been running as the national Large Research Infrastructure (LRI) EU-ARC.CZ supported by the Ministry of Education, Youth and Sports of the Czech Republic. The staff of the node is an interdepartmental (together with the dept. of Solar physics) team of international researchers, post-docs and a technician. The Head of the node (P. Jáchym who is also the PI of the LRI project), together with one researcher and one post-doc are members of the GPS dept. They focus mainly on the user support activities, but also on the observations and the research in extra-galactic areas. Among the main support activities are Phases 1 and 2 of the preparation of observing proposals, quality assurance (QA) analysis of acquired ALMA data, further analysis of the delivered data when required by PIs of the observing projects, face-to-face consultations, participation in ALMA software testing and end-to-end testing, and educational activities. During the QA, the LRI staff assess whether the acquired observing data meet the parameters required in the projects (especially the spatial and spectral resolution and sensitivity). To do this, they perform either a full manual data reduction or a Weblog Reviewing for pipeline calibrated projects. To process the data, the LRI uses the HPC computer cluster OASA in Ondřejov. The processed data are sent to the project authors via the headquarters of the European ALMA network at ESO (European Southern Observatory). Thanks to seminars, workshops, lectures and other promotional activities organized by the LRI, the awareness of the Observatory in the Czech Republic has increased as well as the number of submitted observing projects, in which scientists from the Czech Republic participate.

Fig. 7: ALMA antennas observing the Milky Way's centre. (Credit: P. Horálek/ESO)

Our team members of the node also participate in ALMA development – in collaboration with the central node of the European ALMA network at ESO, they developed the *Imaging Script Generator* code for an automatic creation of a script template for imaging interferometric data using CASA software. This tool became a standard part of the software toolbox (CASA extension) used by the ARC staff. To extend the ALMA user base in the Czech Republic as well as in the neighbouring countries, the node team organizes workshops, seminars and conferences. E.g., in April 2017, a "Joint Pre-Cycle 5 ALMA workshop" was organized together with the Toruń Astronomical Centre at Nicolaus Copernicus University, Poland. Also, we coordinated the preparation of the Special Section 20 "Science with ALMA: Discoveries, Priorities and User Support" at the large international conference EWASS 2017 held in Prague in June 2017. Within the EU ARC network, the node co-organized, together with ESO, the annual all-hands meeting in 2018 which took place in the Czech Republic for the first time. In 2019, our node member participated as a Technical secretary at the ALMA Proposal Review Committee meeting. In 2019, the PI of the LRI project prepared successfully a project "EU-ARC.CZ Cluster for Data Processing from the ALMA Observatory" for upgrade and modernization of the OASA HPC cluster, which will be funded in 2020-2022 from the OP RDE Programme, Call No 02_18_046, Research Infrastructures II.

Besides the node duties, the team also participates in research grant projects and focuses on its own projects with ALMA and other radio and millimetre telescopes (APEX, IRAM 30m, NOEMA, ARECIBO, VLA). Within the node, the first successful Czech ALMA observations were obtained and published. A suite of works about the discovery of molecular gas outside galaxies and a study of optically dark clouds in galaxy clusters were published (e.g., Jáchym et al. 2019; Cramer et al. 2019; Jáchym et al. 2017; Taylor et al. 2017).