# ACROSS THE UNIVERSE

## Research at the Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

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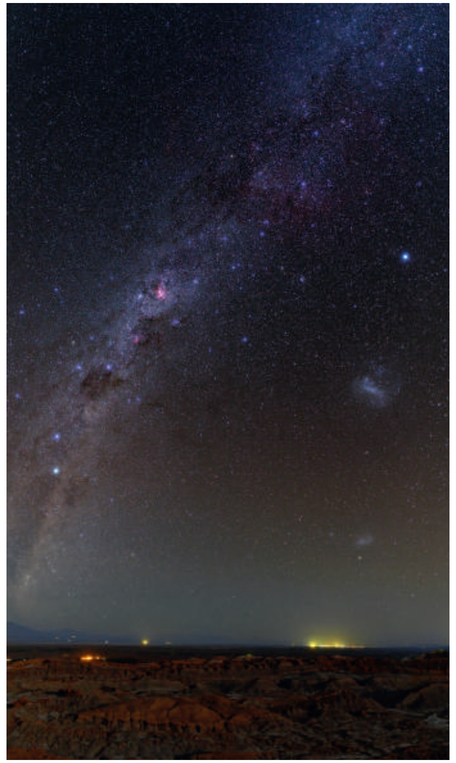

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Warsaw 2020

Across the Universe.
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Photo page 1: ESO/B. Tafreshi (twanight.org)
Photo back cover: Composite image of the active galaxy Centaurus A.
Credits: X-ray - NASA, CXC, R. Kraft et al.; Radio - NSF, VLA, M. Hardcastle et al.; Optical - ESO, M. Rejkuba et al.

Layout, graphic design and printing: Wydawnictwo Aleksander

Published by: Nicolaus Copernicus Astronomical Center
of the Polish Academy of Sciences

The project financed by the
Polish National Agency for Academic Exchange
under the Foreign Promotion Programme

POLISH NATIONAL AGENCY FOR ACADEMIC EXCHANGE

ISBN 978-83-64273-49-0

Warsaw 2020

WYDAWNICTWO ALEKSANDER
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Dear Readers,

We are offering a book about our institute – the Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences (CAMK PAN). We address it mainly to young researchers: undergraduates, PhD students and postdocs looking for opportunities for the next steps in their scientific career. You will find in it a brief overview of our history, and a presentation of our current activities. As you will see, our interests cover a broad range of subjects in observational astronomy, theoretical astrophysics, computational astrophysics, and instrumentation. We are also involved in many large international projects. This creates an environment enabling young people to participate in research activities which best match their characters and passions. We hope to draw your attention to the possibility of including CAMK PAN into your sphere of interest.

***Piotr Życki, Director***

Photo P. Życki

**Michał Różyczka, Piotr Życki**

# CAMK PAN: past, present and future

The history of our institute dates back to 1956 when the Polish Academy of Sciences (PAS) founded the Institute of Astronomy (IA PAS). IA PAS consisted of three units referred to as Astrophysics I in Toruń, Astrophysics II in Warsaw, and the Astrometry and Celestial Mechanics Laboratory in Poznań, all of them closely collaborating with university observatories in those locations.

The first director of IA PAS was a renowned Poznań astronomer, Prof. Józef Witkowski. The second director, Prof. Stefan Piotrowski, headed the all-Polish initiative to erect the Central Astronomical Observatory (CAO) as a monument to celebrate the approaching 500th birthday of Nicolaus Copernicus. The project advanced until the late 60's, when Poland fell into an economic crisis, and the financial support for CAO was cancelled. However, Polish astronomers did not give up, and proposed an entirely new vision.

In March 1970 Drs. Bohdan Paczyński and Józef Smak suggested transforming IA PAS into an institute for theoretical studies in astrophysics. The basic idea behind their proposal was to create a meeting place for astronomers from both sides of the Iron Curtain which was then separating the Soviet Union's sphere of influence from the West. Their project was successfully completed owing to the help of a twin US initiative. In May 1972 the President of the National Academy of Sciences (NAS), Prof. Philip Handler, and his Polish counterpart, Prof. Jan Kaczmarek, signed an agreement binding NAS to secure US funds, and PAS to erect the premises of the institute.

The cornerstone laying ceremony took place on 19th September 1973, shortly after the extraordinary General Assembly of the International Astronomical Union held in Poland to commemorate the 500th birthday of Copernicus. With the help of Dr. Charles R. O'Dell, a representative of NAS, additional funds were raised in US for the purchase of a hi-tech computer PDP 11/45. On 11th February 1976, IA PAS was officially renamed Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences (Polish abbreviation: CAMK PAN)). By then, the Poznań Laboratory had joined the Polish Space Research Centre.

The present CAMK building was released for use in May 1978, and a brief period of vibrant research activity begun. Tens of foreign visitors were hosted annually, including scientists as famous as Michel Mayor, Yakov Zeldowich or Kip Thorne. It all ended in 1981 due to another, even deeper economic crisis followed by a military crackdown. The scientific life at CAMK was never extinguished, however it could gain momentum only after Poland became a democratic country in 1989.

The early 1990-ies brought a new important element to the policy of funding scientific research in Poland, namely a grant system for financing the best proposals. Even though the general financial situation of science was quite bad then, the grant system introduced an important motivational element and created new opportunities, for example, for international collaboration. These stimulated quite significantly the scientific life of CAMK scientists.

Further policy developments created opportunities to fund instrumentation and infrastructure. Together with European funds, available after Poland joined the EU in 2004, this enabled CAMK to join the South African Large Telescope (SALT) consortium, contribute to the Herschel and Integral satellite observatories, join the H.E.S.S. collaboration and contribute to the infrastructure. CAMK researchers could apply for European Research Council (ERC) grants, Marie Skłodowska-Curie fellowships and other programmes. With additional funds from the national budget all this created the possibility to start running our own infrastructure projects, like the Solaris network of robotic telescopes (four 0.5-m telescopes located in Argentina, South Africa and Australia) and BRITE-PL – two, out of the six small BRITE satellites for observing bright stars (constructed mainly by engineers from the Space Research Centre of the Polish Academy of Sciences), together with a ground station on top of the CAMK main building.

Finally, all this enabled us to go back to the original idea from 1960-ies, that of CAO, which in the present realization has, coincidentally, a very similar acronym, OCA (Observatory Cerro Armazones) and is being built by CAMK in Chile. The main instrument will be a 1,5 m class telescope with a number of smaller telescopes, and the main objective of the work done there will be construction of the successive rungs of the cosmic distance ladder.

New types of projects include cooperation between science and industry in developing new hardware for scientific activities. These include projects related to gravitational wave detection (VIRGO/LIGO collaboration) and astroparticle physics (AstroCeNT unit of CAMK). All of the above projects, and more, are described in the following chapters of the book.

>> Astrophysics I unit of CAMK PAN (marked with a circle) is located in the historic center of Toruń – the city where Copernicus was born. Photo: Wikimedia Commons

**Paweł Ciecieląg**

# Computational Department

Our institute has always been at the forefront of information and communications technology in Poland. Thanks to prof. Bohdan Paczyński, already in 1975 CAMK PAN obtained one of the first minicomputers in eastern Europe - the PDP-11/45, (Fig. 1), and the computational department was established.

Astronomers, notably prof. Bohdan Paczyński and dr. Maciej Kozłowski (the head of CAMK computing department from 1987 to 1999) played a key role in connecting Poland to the Internet, with CAMK PAN being one of the first connected institutions. Later, dr. Kozłowski became one of the directors of a new institution coordinating academic networks and the Internet in Poland - the NASK (Naukowa i Akademicka Sieć Komputerowa), located for many years at the CAMK PAN site. Over the years the computational department has changed to match the growing needs of astronomers. Currently our team consists of eight people supporting over one hundred astronomers and PhD students. Every day we help to solve both hardware and software problems, while keeping the local area network infrastructure operational.

### Local area networks

Our network spans three locations: the main building in Warsaw, the Toruń unit, and AstroCeNT in Warsaw. The backbone of the network consists of 9 state-of-the-art switches and optic fibers. The majority of the servers are virtualized and mirrored. Such topology assures constant working conditions with minimum shutdowns. Also it allows fast deployments of new servers and new functionalities without restructuring the backbone itself. The user disk area consists of about 100TB of file space for general use (with backup). There are about 200 workstations (desktops and laptops) connected either by 1Gb/s ethernet or eduroam wifi network. Linux is the dominant operating system for scientists at CAMK although MacOS and Windows are present too. We have four heavy-duty printers/scanners that are available for employees and students.

>> Fig. 1: PDP-11/45 installed at our institute in 1975. Standing at the computer is Prof. Philip Handler, the then President of the U.S. National Academy of Sciences. Photo taken at the opening ceremony of CAMK PAN.
Image credit: CAMK archive.

We host more than 30 websites dedicated to various projects. Scientists have at their disposal also a number of general services to support their work: gitlab (software development), redmine (project management), indico (event management), koha (library catalogue). Furthermore, we offer video-conferencing solutions, both in terms of licensed software and in hardware (H.323/SIP terminals). One of our recent enterprises is a major reorganization of the local area network at the OCA observatory in Chile operated by prof. Grzegorz Pietrzyński's group.

### Computational facilities

Both the Warsaw and Toruń units have dedicated server rooms equipped with UPS units and air conditioning. The computational cluster in Warsaw is our largest facility (Fig. 2). At present it consists of 45 computational nodes with 864 CPU cores in total. Some nodes are equipped with modern GPU (Graphical Processing Unit) accelerators. The nodes are connected with Infiniband network (40-100 Gb/s). Computational resources are facilitated by a high performance cluster file system of size 550 TB and total throughput of 2.5 GB/s. The cluster is ideally suited for massively parallel applications. Examples of the most computationally demanding applications include stellar evolution, dynamics of star clusters and dwarf galaxies., magnetohydrodynamic simulations of accretion disks, simulations of magnetic reconnection in relativistic plasma, and detection of gravitational waves. The cluster is being continuously expanded thanks to the grants of CAMK scientists. The most recent acquisition is a high performance, deep learning GPU system with 8 Nvidia V100 cards, 32 cpu cores and 768 GB of RAM which is used by the gravitational-waves group to develop machine learning methods for data analysis.

The Warsaw server room houses also another cluster which is dedicated to the Cherenkov Telescope Array (CTA) and the High Energy Stereoscopic System (H.E.S.S.) projects. It consists of 14 nodes, 400 CPU cores, 400 TB of storage space interconnected with 40 Gb/s Infiniband network. It is used to simulate the development of atmospheric air showers caused by high energy particles and gamma-ray photons, and also to simulate the process of detection of Cherenkov light from such showers by arrays of imaging atmospheric Cherenkov telescopes (IACTs). The cluster has been integrated into the Polish grid infrastructure (PL-Grid) and the European Grid Infrastructure (EGI) since 2012.

The Toruń unit of CAMK PAN has a smaller, general purpose cluster composed of 8 nodes with 288 CPU cores interconnected with 56 Gb/s Infiniband network. The total storage space is 140 TB. It is used for calculations of radiation transfer and excitation of molecular lines in moving stellar envelopes of evolved stars and red novae.

For many years CAMK PAN has collaborated with the main computing centers in Poland as well as operator of the Polish national grid infrastructure - the PL-Grid. The results of this collaboration are common enterprises, like development of domain grid AstroGrid-PL and consortia within CTA and gravitational waves projects. Our staff supports scientists at CAMK in using PL-Grid which enables free access to the main supercomputing centers in Poland.

Team members: Jerzy Borkowski, Paweł Ciecieląg, Roman Feiler, Artur Gawryszczak, Krzysztof Leszczyński, Zbigniew Loska (head), Stanisław Miszczak, Magdalena Zbyszewska.

>> Fig. 2: Computational clusters in the server room at Warsaw.

**Radosław Smolec**

# Doctoral studies at CAMK PAN

From the very beginning of CAMK, one of its major objectives was to train a new generation of scientists, able to lead international-level research. This goal is accomplished through competitive PhD program that we have been running continuously for more than 40 years now. The first PhD degree was awarded in 1980 to Marek Sikora. The last PhD diploma that we issued holds the number 108.

Starting with the academic year of 2019/2020, PhD students attend the GeoPlanet Doctoral School. This form of training of PhD students was introduced with the new Law on Science and Higher Education to stimulate interdisciplinary research projects. The GeoPlanet Doctoral School comprises seven institutes of the Polish Academy of Sciences: the Institute of Geography and Spatial Organization, the Institute of Geology, the Institute of Geophysics, the Institute of Oceanology, the Institute of Theoretical Physics, the Space Research Center, and CAMK as the leader of the School. We offer PhD topics in astronomy, physics, and Earth and environmental sciences. Our students, while still based at specific institutes and tightly connected to research conducted therein, may attend interdisciplinary lectures, lectures on statistics, philosophy of science or workshops aimed at training communication, presentation or writing skills.

During the last academic year (2019/2020), CAMK hosted 43 PhD students that carried out research in nearly every branch of astrophysics or cosmology. The students are a diverse and international group, and most of them come from abroad. Each year a few new students are selected in an open and demanding competition. Each year a few students receive PhD degree and find postdoctoral positions in renown institutes all over the world, often accompanied with prestigious fellowships. After gaining international and diverse experience, some of them return to their 'alma mater' to establish new research teams and train their successors.

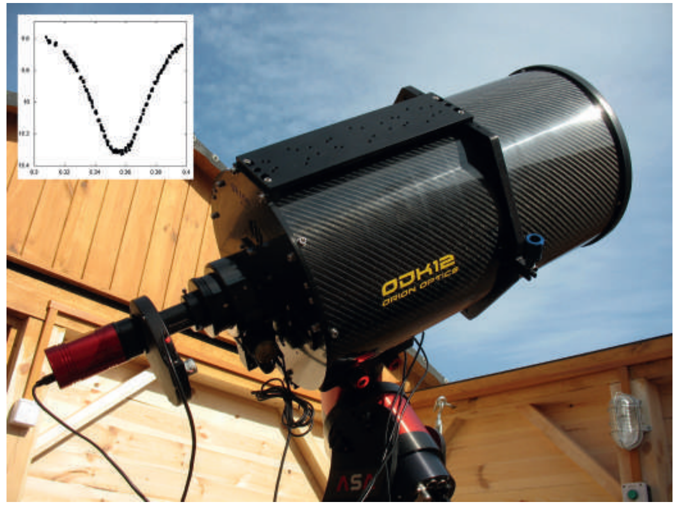
For our students we offer an open, stimulating and friendly environment. Students from outside of Warsaw can live in guest rooms at the Institute. Student offices are shared between 3 to 5 students, and all necessary research infrastructure is provided. A computer cluster at the institute is regularly updated to accommodate the continuously growing need for computer resources. Students have the opportunity to train observational skills using a small, 30-cm telescope equipped with CCD camera, located on the rooftop of CAMK - a good starting point before carrying out observational programs at the world's largest telescopes and observing facilities, to which CAMK has access via international agreements or Poland's membership in the European Southern Observatory. Each year we offer monograph lectures covering a wide spectrum of astrophysical research. Regular institute seminars, lecture series by distinguished guests and weekly Journal clubs supplement our offer.

Still, PhD studies are individual in nature. From the very beginning, the students are expected to conduct research that will finally constitute their thesis. There are many opportunities to support their research. At the beginning most of the students rely on the grants of their supervisors. Once the first scientific results appear, the student may apply for their own research grant(s). Our

>> Academic year 2019/2020. CAMK PAN PhD students Eleonora Veronica Lai (supervisors Barbara de Marco and Andrzej Zdziarski) and Ruchi Mishra (supervisor Włodzimierz Kluźniak). Photo credit: Chandra Shekhar Saraf.

students are very successful in applying for scientific grants at all major funding institutions and agencies in Poland: the Ministry of Science and Higher Education, the National Science Center (NCN), the National Agency for Academic Exchange (NAWA) or Foundation for Polish Science. The ETIUDA (NCN) and Wilhelmina Iwanowska (NAWA) grant schemes allow to conduct part of the research within long internships at prestigious foreign institutions. Our students receive prestigious distinctions and awards for their scientific achievements including scholarships of the President of the Polish Academy of Sciences, scholarships from the Foundation of Polish Science and awards for the best PhD theses (recently including Springer Thesis award).

If you are about to finish your Master's thesis and are interested in research and in astrophysics, do come to our Institute to start a fascinating career in science.



>> Fig. 1: The training telescope, and an obtained by the students light curve oft a W UMa – type eclipsing binary AB Andromedae. Digits on the horizontal axis are fractions of the Julian day 2458718 (2019, August 22); the vertical axis is scaled in V-band magnitudes. Image credit: W. Pych

>> Fig. 2: PhD students, their supervisors, CAMK employees and guests during the conference of Young Researchers at CAMK. Image credit: Chandra Sekhar Saraf

**Rodolfo Smiljanic**

# The Gaia-ESO Survey (and beyond)

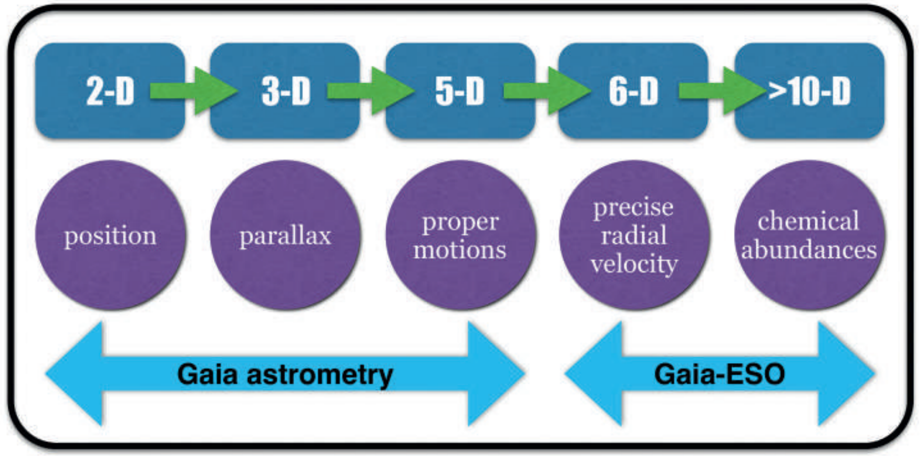
Understanding the processes of formation and evolution of the Milky Way is a fundamental goal of modern astrophysics. Putting together the timeline of events that formed the Galaxy is the goal of "Galactic archaeology".

Our Galaxy contains well defined morphological structures made of stars with different properties. There is a central bulge comprised mostly of old and metal-rich stars, a pressure-supported spherical halo made of old and metal-poor stars, a rotating disc where we can find young metal-rich stars and the spiral arms. Moreover, besides forming its own stars, the Milky Way has also experienced merger events, where smaller, external galaxies added stars that mixed with the Galactic stellar populations.

This research area aims to uncover the formation history of each Galactic stellar population. To do that, astronomers have to sift through stellar fossil records, just like traditional archaeologists go through fossils and other remnants to understand human history. In our case, it is by measuring ages, movements, and chemical abundances of large samples of long-lived stars that we can study the structure and evolution of our Galaxy.

The *Gaia* space mission of the European Space Agency is a game changer in what concerns measuring the movements of stars. *Gaia* is delivering precision astrometry (positions, parallaxes and proper motions) for more than $10^9$ stars. *Gaia* is also obtaining spectra, albeit for a smaller sample of stars (about 150 x $10^6$). However, with ground-based instrumentation it is possible to obtain spectra of higher quality that allow more detailed chemical analyses.

Such was the ambition that motivated the *Gaia*-ESO[1] large stellar spectroscopic survey. This survey obtained medium- and high-resolution stellar spectra, using



>> Fig. 1: The Gaia-ESO Survey complements the astrometry of the Gaia satellite with precise radial velocities and detailed chemical abundances. These data enable multi-dimensional chemo-kinematic analyses that improve our understanding of the formation and evolution of the Galactic stellar populations (inspired on Fig. 2 of Gilmore et al. 2012, the Messenger, 147, 25).

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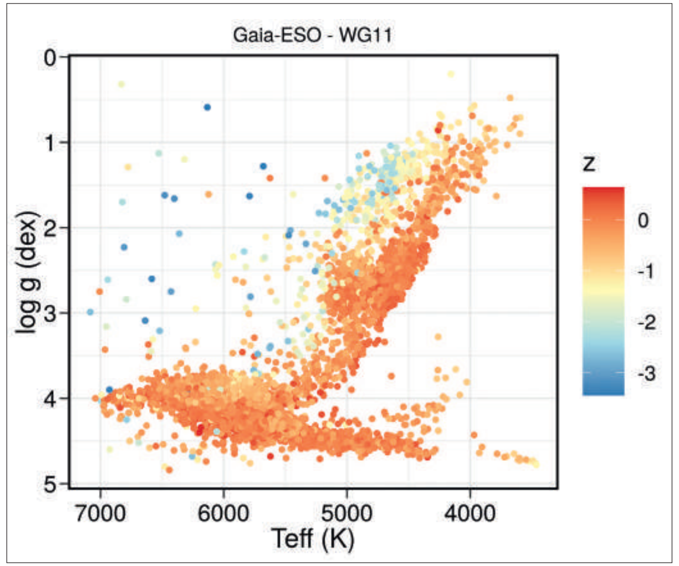
[1] https://www.gaia-eso.eu/



>> Fig. 2: Values of surface gravity as a function of effective temperature for more than 6000 stars determined by WG11 of the Gaia-ESO Survey. The points are color coded according to their metallicities: low-metallicities in blue and high-metallicities in red (see scale on the right).

FLAMES (Fiber Large Array Multi-Element Spectrograph) at the VLT (Very Large Telescope), during 340 nights between 2012 and 2018. In total, 193 182 new spectra were observed and analyzed in combination with about 9000 spectra downloaded from the ESO data archive. The final sample, of more than 115 000 different stars, includes: stars in different evolutionary stages (pre-main sequence, main sequence, and giants), early- and late-spectral types (O, B, A, F, G, K, and M), stars that are part of the Milky Way field, and stars in 15 globular and in 71 open clusters (including also a few star forming regions).

*Gaia*-ESO was specifically designed to observe stars in all the Galactic stellar populations and components observed by *Gaia*. The analysis of the spectra provides chemical abundance information and precise radial velocities to complement the kinematic information obtained from *Gaia* astrometry (Fig. 1). In truth, the scientific goals of *Gaia*-ESO go much beyond Galactic archaeology. The spectra obtained in this project are also meant to contribute to studies of stellar evolution, of star formation, and to follow in detail the lifetime (formation, evolution and dissolution) of open clusters.

To manage such a complex project, a structure containing 20 Working Groups was created. The list of *Gaia*-ESO collaborators includes more than 400 researchers, from all over the world, although astronomers based in Europe are the majority. I am leading Working Group 11, that consists of more than ten different international teams, and is responsible for the analysis of high-resolution spectra of F-, G- and K-type stars (the analysis is described in Smiljanic et al. 2014, A&A, 570, A122). Astrophysical parameters for more than 6000 stars derived by WG11 are illustrated in the diagram of Fig. 2.

As of July 2020, 82 refereed publications have been published by the *Gaia*-ESO consortium; 48 of them with the participation of the group at CAMK PAN. Even though the analysis of the spectra obtained by *Gaia*-ESO is expected to be completed by the end of 2020, exploitation of the Survey results will continue for at least a few more years. A lot of exciting science, in Galactic archaeology and other fields of stellar astrophysics, remains to be done. Related opportunities are periodically made available in the form of summer research internships and PhD projects at CAMK PAN.

In the near-term future, our group at CAMK plans to develop an innovative analysis system specifically designed to deal with large samples of spectra. The system will combine the traditional physical modeling of stellar spectra with machine learning methods of analysis. It is our ambition to use this system to further refine and expand both the amount and quality of the chemical information that can be derived from already existing (and future) sets of stellar spectra. With these new results, we will conduct comprehensive studies of the Galactic stellar populations, helping to improve our understanding of Galaxy formation and evolution.

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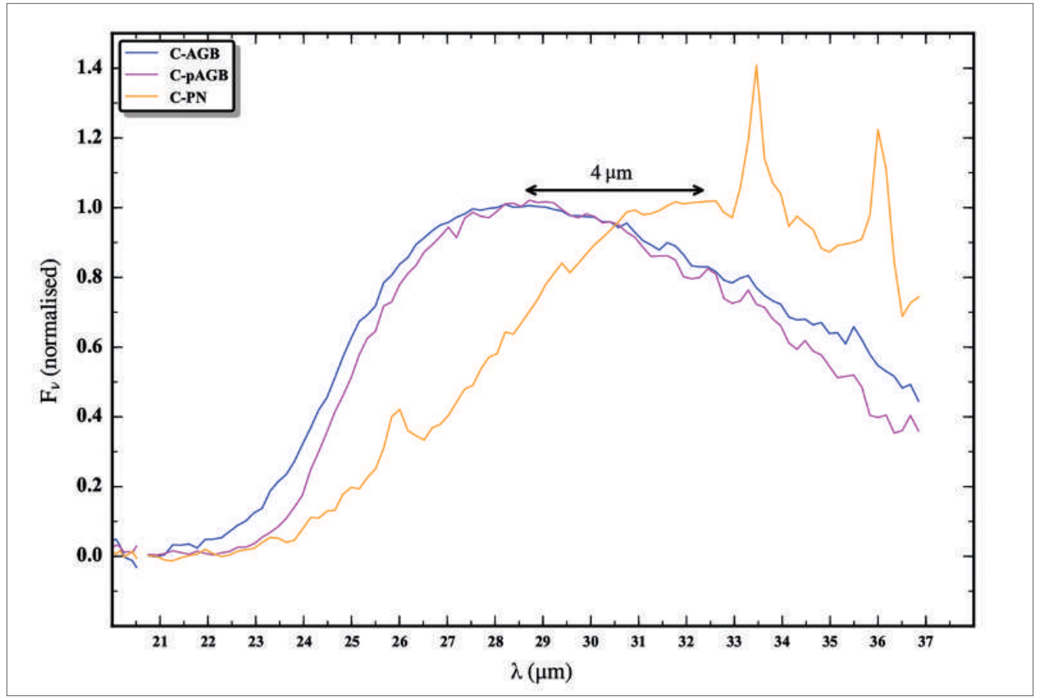
### Ryszard Szczerba, Mirosław Schmidt

# Infrared and sub-millimeter astronomy

The infrared and sub-millimeter domains of the electromagnetic spectrum provide information about the interstellar matter from which stars and planets originate, and about the interstellar chemical processes capable of producing surprisingly complex organic molecules.

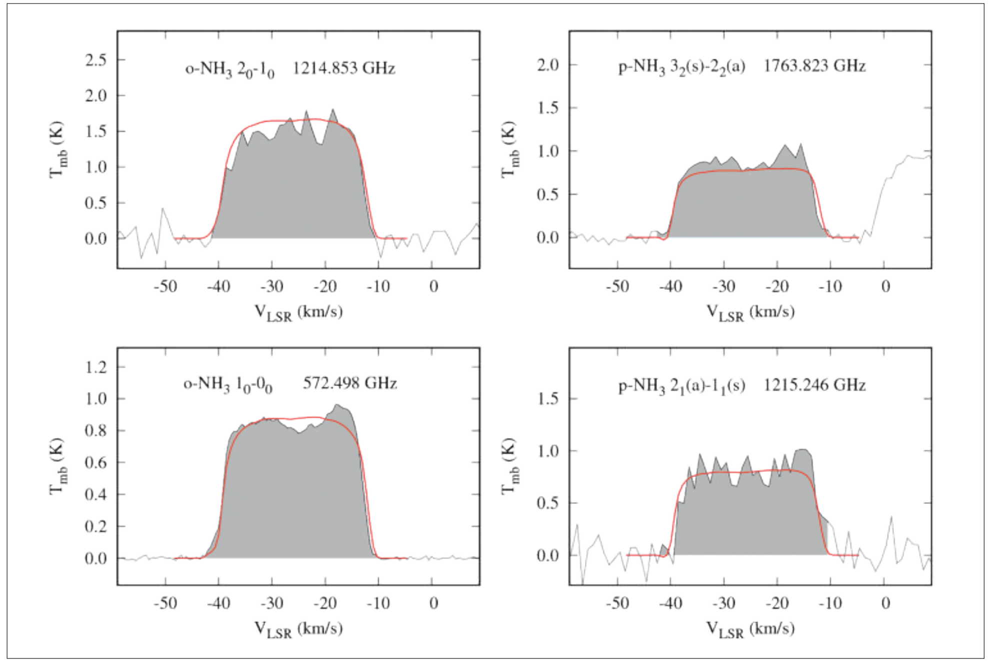
Observations in the infrared (IR) and in the sub-millimeter range are not possible from the ground due to absorption by the Earth's atmosphere. To conduct them we need to use satellites carrying scientific instruments in space, which makes infrared and sub-millimeter astronomy a rather expensive branch of science. Additional constraints are put by the limited period (usually only a few years) of satellite operation, since instruments, and especially their detectors, must be cooled to temperatures close to 0 K, and the amount of coolant (liquid helium) is obviously finite. Cooling is crucial, as at 50 K the satellite itself radiates in the far-IR around 60 µm, while at 5 K that maximum falls in the submm range around 600 µm. As a result, a spacecraft which is not appropriately cooled gets blinded by its own emission.



>> Fig. 1: Normalized median profiles of the 30 µm dust feature for AGB and post-AGB stars, as well as PNe from MW, SMC and LMC. The shift in the central wavelength is about 4 µm.

Our group from the CAMK PAN branch in Toruń has been studying the cool Universe from the launch of the Infrared Space Observatory (ISO) in 90's. Here, we briefly describe the most important achievements of our group, related to Asymptotic Giant Branch (AGB) stars, post-AGB stars, and planetary nebulae (PNe). Such objects are surrounded by molecular and dusty material ejected by stars in the final stages of their evolution. All stars are born oxygen-rich, and end their lives being either still O-rich, or carbon-rich due to carbon nucleosynthesis and mixing to the stellar surface. The standard scenario (assuming equilibrium conditions) predicts that the less abundant element (C or O) is completely exhausted for the formation of CO, while the remaining element determines the ongoing chemistry in the material ejected from the stars (oxygen, or carbon-based). Therefore, it was surprising to find evolved stars with simultaneous signatures of both chemically diverse compounds (so called “mixed chemistry”).

The first infrared satellite IRAS (InfraRed Astronomical Satellite) which performed photometric survey of the whole sky at 12, 25, 60 and 100 μm, was launched in January 1983, and operated only for 10 months. Among the most important achievements of this mission were discoveries of ultraluminous infrared galaxies, galactic cirrus, and Vega type debris disks. The spectroscopic capabilities of this mission in mid-IR allowed to discover the puzzling 21 μm dust feature (present only in post-AGB stars, and still unidentified), and the so called silicate-carbon stars (evolved stars showing simultaneous presence of carbon- and oxygen-rich material). Our group resolved the problem of silicate-carbon stars by showing that they are binary systems in which a C-rich AGB component (responsible for C-rich material) has an O-rich companion (responsible for O-rich compound).



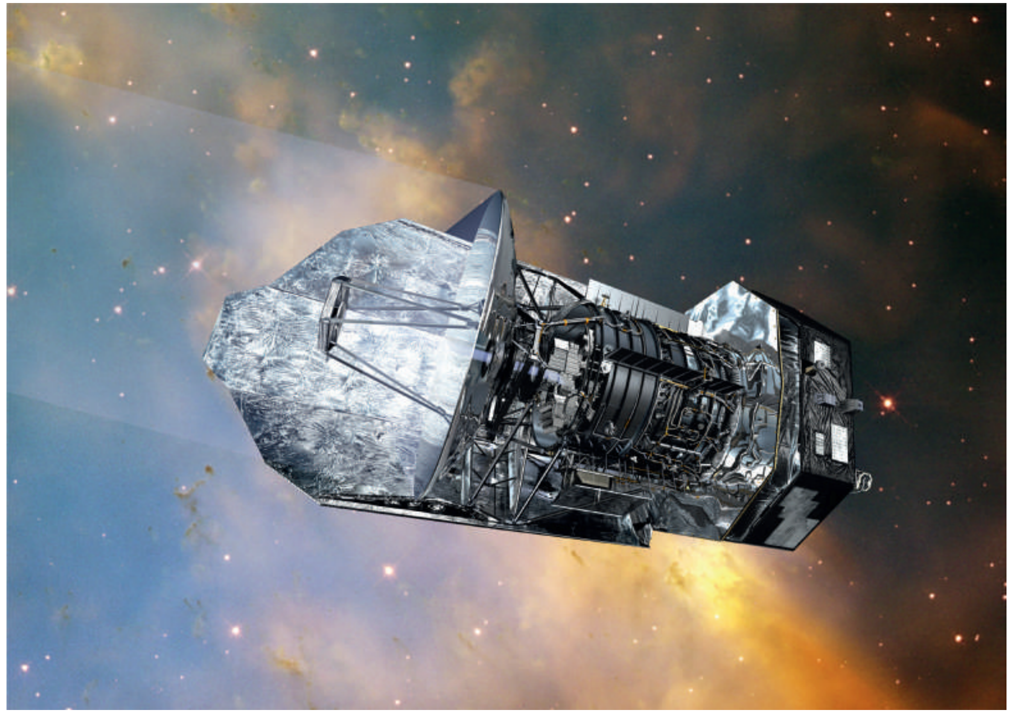
>> Fig. 2: Herschel observations of rotational transitions of ortho- and para-NH$_3$ in the circumstellar envelope of the archetype C-rich star CW Leo. Emission profiles are overplotted with theoretical profiles (red lines) from the best fit models computed separately for each ammonia spin isomer.

The Infrared Space Observatory was launched in November 1995 and stopped observations in April 1998, when all liquid helium was depleted. This satellite operated in the range from 2.5 to 240 μm. One of its most important discoveries was the detection of extrasolar crystalline silicates (O-rich dust in crystalline form). Crystalline silicates were discovered also in so called [WR] PNe whose central stars are C-rich, and H-poor. Our group was involved in the analysis of these PNe, as well as in a detailed analysis of dust contents in post-AGB objects with 21 μm and the associated 30 μm spectral features. We argued in favor of MgS as a carrier of the 30 μm feature.

The Spitzer Space Telescope (SST) started its over 16 years long cosmic odyssey in August 2003 and stopped its cold phase observations in May 2009, while observations in the near-infrared (below 5 μm) remained possible, and were continued until the end of January 2020 (sic!). The telescope provided photometry from 3.6 μm up to 160 μm, and spectroscopy in the mid-IR. The high sensitivity of its instruments allowed to detect the 21 μm dust feature in post-AGB objects in Small and Large Magellanic Clouds (SMC and LMC), as well as fullerenes ($C_{60}$ and $C_{70}$) in PNe from MW and SMC. As far as the fullerenes are concerned, we showed that in space they are formed in an H-rich environment, opposite to what is expected from laboratory experiments. The large number of 30 μm sources detected with SST allowed us to show that the average profile of this feature is similar for AGB, post-AGB and PNe in galaxies of different metallicity, while its central wavelength is consistently and significantly shifted to longer λ's in the case of PNe (see Fig. 1).

So far the largest (3.5 m diameter), and most sensitive mission, the Herschel Space Observatory (HSO) operated from May 2009 until the end of April 2013. One of the crucial results of this mission was the census of oxygen and water occurrence in space. Surprisingly, the widespread occurrence of water vapor and ammonia was confirmed also in C-rich stars. Fig. 2 shows an example of ammonia detection in the C-rich star CW Leo together with model profiles obtained by our group. Our work removed the discrepancy in the estimation of ammonia abundance in circumstellar envelopes by invoking the so called infrared pumping of NH$_3$.

Presently, we are still analyzing SST and HSO data, while working on another space mission in the mid- and far-IR called SPICA, planned to be launched after 2030.



>> CAMK PAN contributed to the successful mission of the infrared/submillimeter satellite Herschel. Image credit: ESA, NASA, STScI.

**Krzysztof Hełminiak**

# *CRÉME de la crème* of eclipsing binaries

More than 50% of the stars are in fact binaries, i. e. gravitationally bound stellar pairs whose components revolve around a common center of mass. Studying such systems brings invaluable information employed in nearly every branch of astronomical research.

Among the many various classes of objects studied by stellar astrophysics, the *detached eclipsing binaries* (DEBs) have a special place. The detached configuration means that two stars do not interact with each other (except gravitationally), and evolve as if they were single. The components of a DEB eclipse each other at regular time intervals, and we observe these events – the eclipses – as characteristic drops in total brightness of the pair. We can also directly observe the orbital motion of the components, by measuring changes in their radial velocities (RV). This motion is determined by Kepler's laws, and gives us information about the masses of the two stars. On the other hand, the overall shape of the eclipses, including their duration and depth, depends on the sizes of two stars, and how hot they are.

All these observations combined allow astronomers to measure parameters that are difficult or even impossible to obtain in a different way, mainly stellar masses, sizes, and temperatures. They can later be used to calculate other parameters, like age and distance to the system. All these properties can be measured with very high precision, and this makes DEBs one of the most important and useful objects for stellar astrophysics, and astronomy in general. They are used in such fields as stellar structure and evolution, star formation , the cosmic distance scale, extrasolar planets, asteroseismology, or even for testing the General Relativity.

Since DEBs may contain stars of almost any kind, they offer the possibility of studying unusual, relatively rare, or poorly understood classes of stars, such as pre-main-sequence (PMS) stars, low- or high-mass stars, evolved giants, pulsators, multiple systems, etc. Unfortunately, despite tens of thousands of DEBs being known, only a relatively small number of them has been studied in sufficient details, and very few of those belong to the aforementioned classes. This need for new, well-studied cases of unusual DEBs was the main driver behind the Comprehensive Research with Échelles on the Most interesting Eclipsing binaries (CRÉME) project, which was initiated in 2011, and is now run at CAMK PAN.

Observations for the CRÉME project were performed between 2011 and 2018 on 15 different high resolution échelle spectrographs at 13 telescopes around the world, mainly in Chile, but also in Japan, the Canary Islands, and Hawaii. Over 360 DEBs were observed, and about 4000 spectra were taken, mainly in order to calculate the RVs, but also for the purpose of independent determination of temperatures and metal content through spectral analysis. The RVs were later combined with available photometry, initially from public surveys like ASAS, SuperWASP or TrES, and first, crude estimates of stellar parameters were made. Then, systems that showed interesting characteristics were studied in more details, with more spectroscopic and photometric observations, sometimes supported by other kinds of data (like timing of eclipses, high-angular-resolution imaging, etc.). For that stage we were choosing DEBs that were found to: contain a low- or very-high mass star; contain a star that is too large for the main sequence (either PMS or a giant); are a part of a larger stellar system (a multiple or member of a cluster); have or are suspected to have pulsations; show total eclipses; or allow for extremely high precision of RV measurements. These are the *crème de la crème* of the DEBs.

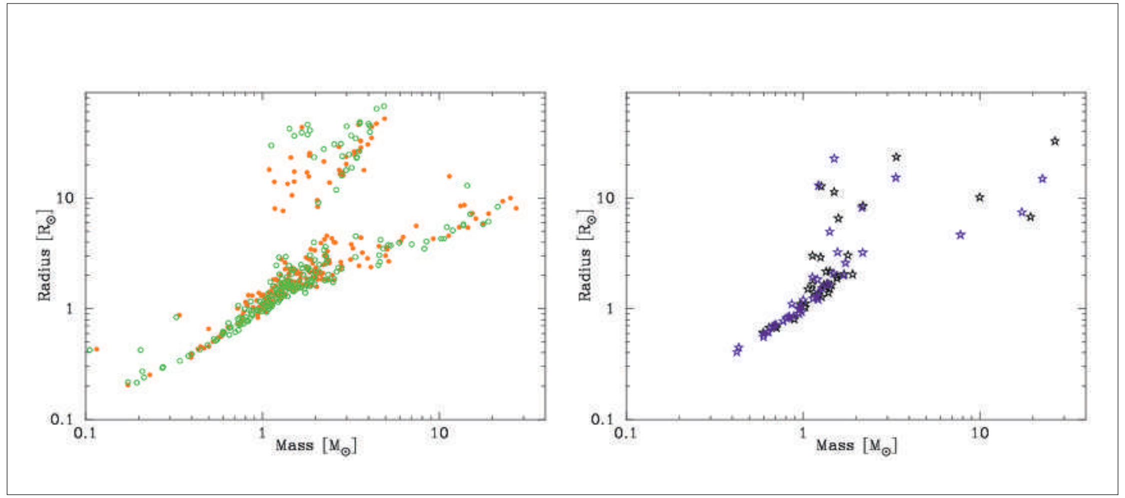
To date the CRÉME project brought a number of exciting results. One of the first were studies of DEBs composed of two low mass (below 0.8 solar mass) stars, like CD-39 325, member of a quadruple system, or AK Fornacis, for which extremely high precision (~0.1%) mass measurements were made. Several other low mass stars were found as secondary companions to bigger, brighter, and more massive primaries. Stars lighter than the Sun are interesting for astronomy, because they constitute the vast majority of the Milky Way, yet their evolution is not fully understood. For example, some of them seem to be too large and too cold in comparison with our models, while others, seemingly identical, are reproduced by the theory pretty well.

Another class of stars prominent in the project are evolved giants and sub-giants. CRÉME delivered some of the first, well-studied galactic pairs of eclipsing giants, like HD 187669, KIC 9246715 with a solar-like oscillator, or V1980 Sgr which exhibits one of the strongest stellar spots known to date, decreasing the flux of one of the components by over 40%. CRÉME results helped to establish an observational boundary for the presence of spots in giants (below 20 solar radii), which may help to constrain models of stellar magnetic fields and spot formation in those stars.

On the other side of the stellar evolution, young PMS stars are also found in DEBs, and obviously are studied within the project. An important example is V1200 Cen, one of the brightest stars of this kind, probably a young quadruple, whose eclipsing components do not match models of stars for the same age (18.5 and 7 Myr). Additionally, CRÉME also contributed to asteroseismology, by providing precise masses and radii for several cases of various pulsating stars. For example, out of four precisely measured γ Doradus type pulsators known in DEBs, two (KIC 10031808 and KIC 10987439) were identified within CRÉME. In our sample we also found δ Scuti and solar-like pulsators.

The list of interesting results goes on. Even though the spectroscopic campaign is basically finished, the analysis of the vast amount of gathered data is still ongoing. The project is also exploiting photometric capabilities of the recently launched TESS satellite, which observes about 240 of CRÉME targets. We also continue dedicated photometric observations with ground-based telescopes, like the *Solaris* network, operated by CAMK PAN. New findings are published regularly.

Team members: Krzysztof Hełminiak (head), Maciej Konacki, Frédéric Marcadon and Ayush Moharana.



>> Fig. 1: Masses and radii of the components of the DEBs, taken from the DEBCat catalog (left, with CRÉME omitted), and of a sample of CRÉME systems modeled so far (including entries in DEBCat and unpublished results). Primary and secondary components are marked with different colors.

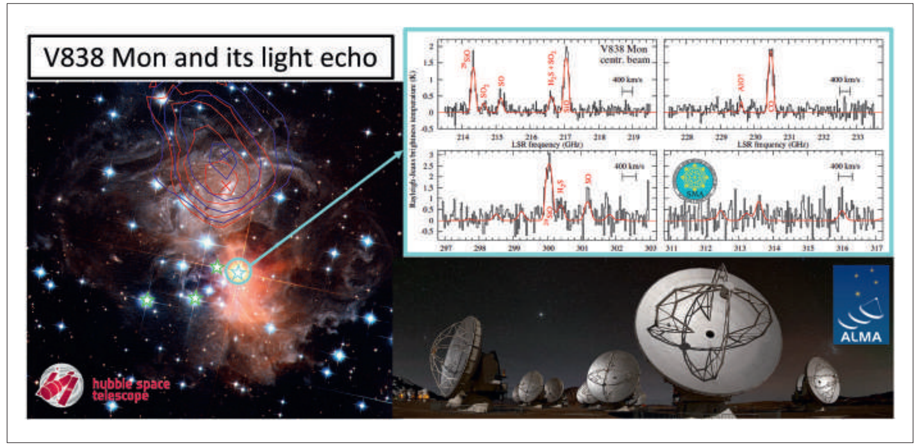
**Tomasz Kamiński**

# Red novae

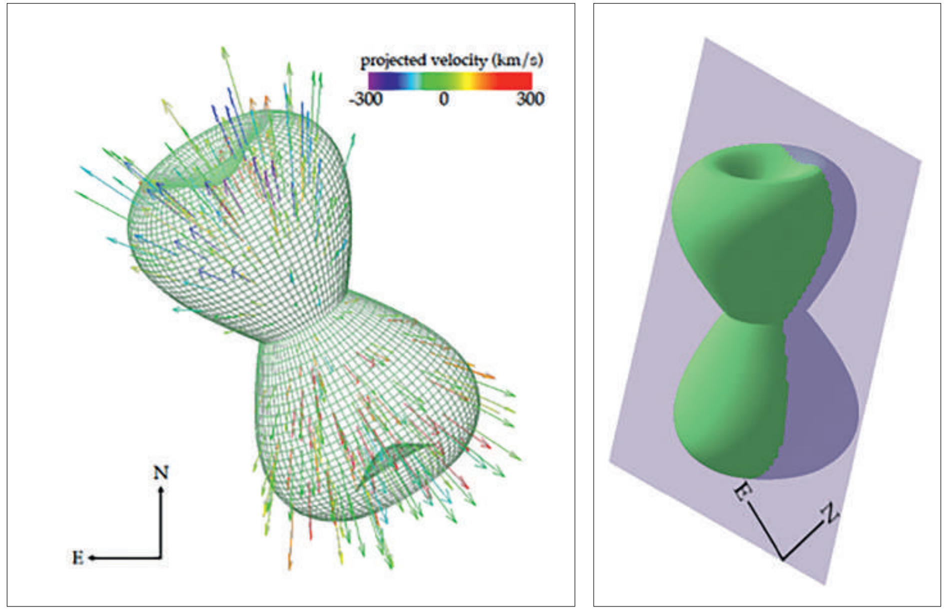
Astronomers have known for a long time that stars can collide and merge, giving birth to a new star. Such can be the fate of stars similar to the Sun, as well as more evolved subgiants or red giants. Observations of these spectacular events give us insight into complicated physical phenomena occurring during the final phases of binary systems.

Reasons why normal stars merge are very poorly understood, but most likely they are very different than those leading to the merging of black holes or neutron stars. Their merger is a straightforward consequence of the emission of gravitational waves, whereas the mechanisms leading to collisions between less compact and less massive stars are more convoluted. Numerical simulations of systems of non-compact stars exist but they are inevitably incomplete, and often leading to contradictory results. Our group at the Toruń branch of CAMK PAN conducts multiwavelength observations aimed at understanding the causes and outcomes of collisions between non-compact stars.

It has been long suspected that many well-known, and also exotic types of stars, could have been created in stellar-merger events. Among these objects are blue stragglers, R-type carbon stars, R Coronae Borealis stars, rapidly rotating FK Comae stars, the progenitor of the famous supernova SN1987A, and many others. In the case of these merger candidates, the collision must have taken place a very long time ago, typically from hundreds to millions of years ago. It would be very hard to identify any direct signatures of that event and convincingly demonstrate observationally that such a merger indeed took place.



>> Fig. 1: V838 Mon, which erupted in 2002, is the most famous red nova. It owes its popularity to the iconic images of its light echo (left). The echoing material is not directly related to the star. It is rather a dusty interstellar medium which is part of a molecular cloud (shown in red and blue contours of CO emission) and which surrounds a young open cluster indicated by star symbols. Millimeter-wave spectra of V838 Mon taken with the Submillimeter Array (top right) reveal rich molecular environment formed after the merger. This molecular material is currently being imaged with ALMA (lower right) to reveal details of the collision process at a resolution of 20 mas.
Image credit: HST, ALMA, T. Kamiński.



>> Fig. 2: A three-dimensional reconstruction of the structure of the merger remnant in V4332 Sgr (a red nova from 1994) based on ALMA observations in molecular lines, mainly of CO 3→2. The bipolar outflows have been predicted to form by some simulations of stellar collisions, but only ALMA was able to provide spatially resolved images of a red-nova remnant 25 years after the merger.
Image credit: T. Kamiński.

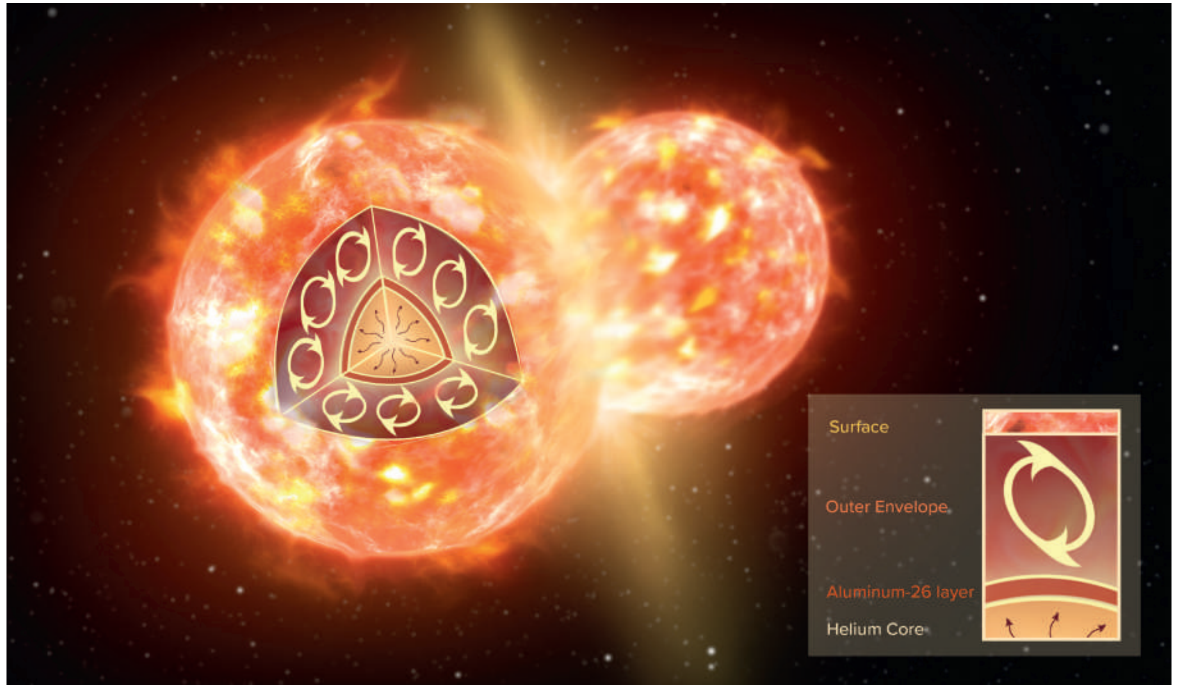
Very recently, however, we have identified a group of objects, often named *red novae* or *red transients*, which undergo cataclysmic collisions before our eyes, that is, we observe them during (and, in rare cases, even just before) the merger event. Our work was essential in explaining eruptions of red novae as optical manifestations of mergers of non-compact stars. We discovered and characterized several objects in this group. Currently, we know of five Galactic red novae but expect to discover many more in the coming years. In the Local Group, over a dozen of objects of this type has been found. In a galaxy like ours, two bright red novae per decade are expected.

Because remnants of red novae contain information about the physical processes that have led to the collision, they are the primary targets for our team. Just after the collision, each red nova becomes very cool, and its surroundings become enriched in cold molecular gas and dust. From the existing observations, it appears that the structure of these cool environments is very complex. The remnants are often composed of a disk or a dusty torus immersed in multi-phase outflows. The history of the past stellar collision is written in the properties of these structures. Decoding this history is of prime interest to our group. Through observations of red novae and their remnants we can learn, for instance, how much angular momentum is deposited in the circumstellar structures and what fraction of it stays in the newly-formed star. These post-merger quantities can then be compared to the total angular momentum of the system prior to the collision. As mentioned, simulations are not able to reliably predict how the angular momentum (and some other quantities) is redistributed in the merger remnant. We aim to fully characterize red nova remnants and decode the processes responsible for stellar collisions.

Because most of the material surrounding red novae is cool and the gas has a molecular component, the investigation of merger's aftermath is conducted mainly in the infrared and millimeter-wave ranges. These wavelength regimes contain spectral signatures (i. e. rotational and ro-vibrational transitions) of many molecules. From these, it is straightforward to determine the motions of material surrounding the star. In ongoing work, we also apply a brand new approach to observations of red novae in which we use interferometric imaging techniques to obtain detailed maps of the regions where the stars had collided. For example, we use the Atacama Large Millimeter/submillimeter Array (ALMA) which combines light from 43 radio antennas to obtain maps at a level of detail achievable by a single telescope with a diameter of 16 km. In the infrared, we currently use two interferometers, *Gravity* and *Matisse*, which have been very recently installed at the Very Large Telescope Interferometer (VLTI). These imaging efforts are set to deliver unprecedented observations of newly formed stars and their immediate surroundings, allowing us to solve many mysteries related to mergers of non-compact stars.

The formation of molecules is an important diagnostic tool to recognize red novae and their remnants. The molecular content – whether it is studied at optical, infrared, or millimeter wavelengths – is very bizarre. The molecular inventory can be surprising, for example combining species typically known to be present either in oxygen-rich or carbon-rich stars but hardly ever together. Some species, e.g. CrO, are only seen in red-nova remnants, and we were the first to observe them. Molecules containing rare isotopes have been also found in red-nova remnants, including $^{26}$AlF which was the first radioactive molecule observed in space. These chemical peculiarities allow us to investigate the nature of the progenitor systems of red novae. Apart from their wonderful bizarreness, the red nova remnants provide us with a view of molecular environments formed out of shocked gas on time scales of weeks to centuries. We currently investigate how molecular observations of red novae can be used to learn more about the most extreme forms of astrochemistry that may occur in a wide range of eruptive objects.

Team members: Tomasz Kamiński (head), Mirosław Schmidt and Romuald Tylenda.



>> Fig. 3: A stellar collision in CK Vul was observed in 1670. Its remnant, as observed today, has revealed the presence of a molecule containing the radioactive isotope of aluminum, $^{26}$Al. The presence of this rare species may be only explained if at least one of the stars that collided in 1670 was a red giant with a helium core.
Image credit: NRAO, T. Kamiński.

**Joanna Mikołajewska**

# Symbiotic stars, novae and related interacting binaries

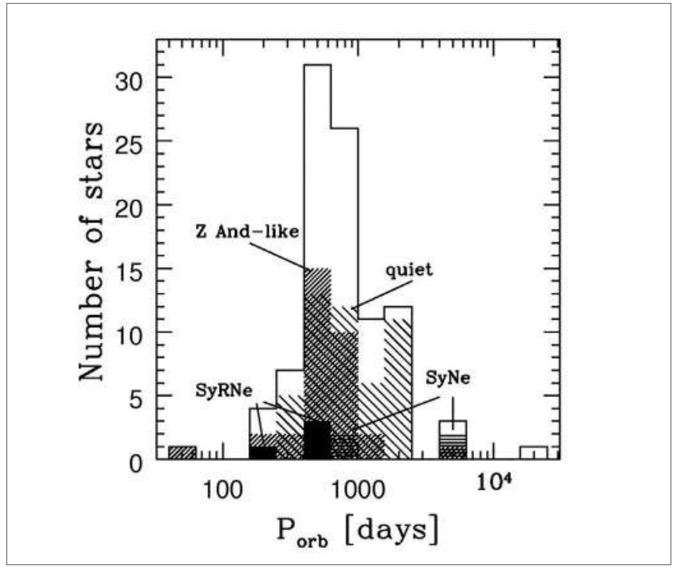
Interactions between components of stellar binary systems abound with fascinating phenomena related to many branches of astrophysics, and even to cosmology. The main objective of my research, carried out at CAMK PAN with my coworkers, are interacting binaries with evolved donors, especially novae and symbiotic stars.

The majority of stars are in binaries, and more than half of them will interact and exchange mass at some point. Stellar models are, however, mostly of single stars and in the majority of galactic population studies the role of binaries is not sufficiently addressed. On the other hand, binaries can have an immeasurable impact in galactic populations and strongly interacting binaries can even impact on ionization in the early universe. Among the most common interacting binaries are those in which a white dwarf (WD) accretes hydrogen-rich material from red/brown dwarf (main-sequence star), subgiant or giant companion.

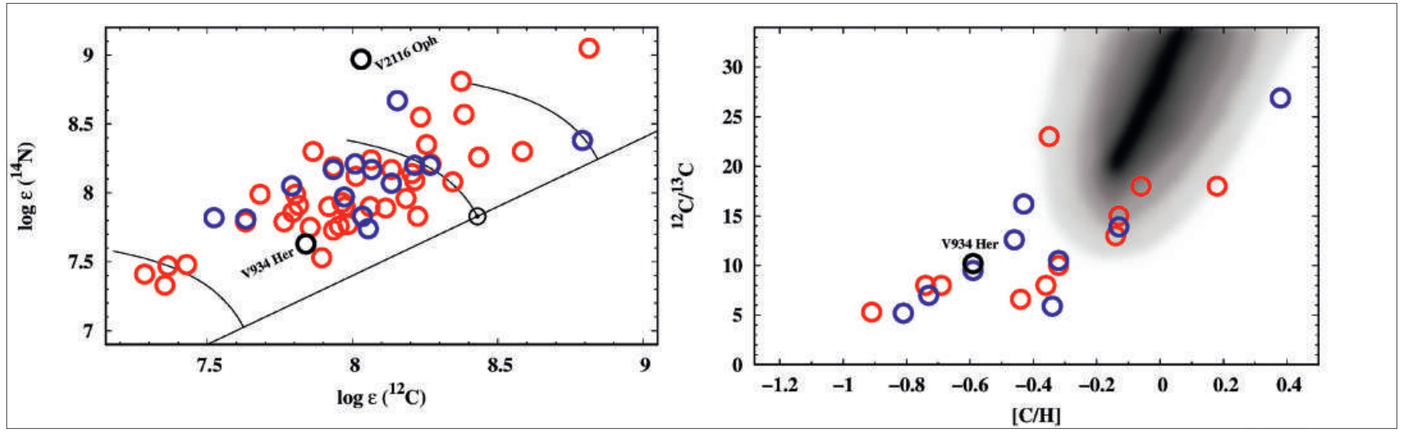
Accretion leads to various outburst phenomena; among the most spectacular are thermonuclear nova explosions. Nova explosions provide large enrichments of interstellar medium in CNO as well as Ne, Na, Al and other intermediate-mass elements, and their study is essential to understand the Galactic nucleosynthesis including the ‘life’ elements. Furthermore, CO novae are the main $^{7}$Li factories in galaxies and they can produce all (and even more) Li observed in excess of that predicted by Big Bang nucleosynthesis.

Symbiotic stars (SySt) are interacting binaries with the longest orbital periods, in which an evolved red giant (RG) transfers material to a hot WD (and sometimes a neutron star).

Studies of these systems are of fundamental importance in understanding the evolution of binaries involving in some phase red giants and accreting white dwarfs, including such exotic and important objects as the elusive progenitors of Supernovae type Ia (SN Ia),



>> Fig. 1: The orbital period distribution for symbiotic stars. The shaded regions denote different populations – the Magellanic and Galactic yellow, disk and bulge.



>> Fig. 2: Left: Nitrogen versus carbon for symbiotic giants. Red and blue circles represent southern, and northern SySt, respectively, and black circles – two SySt with accreting NS. The solid line represents scaled solar abundances, $[^{12}C/Fe] = 0$ and $[^{14}N/Fe] = 0$, and the solid curves delineate constant $^{12}C+^{14}N$. Right: $^{12}C/^{13}C$ versus [C/H] compared with theoretical model predictions (shaded area).
Image credit: C. Gałan.

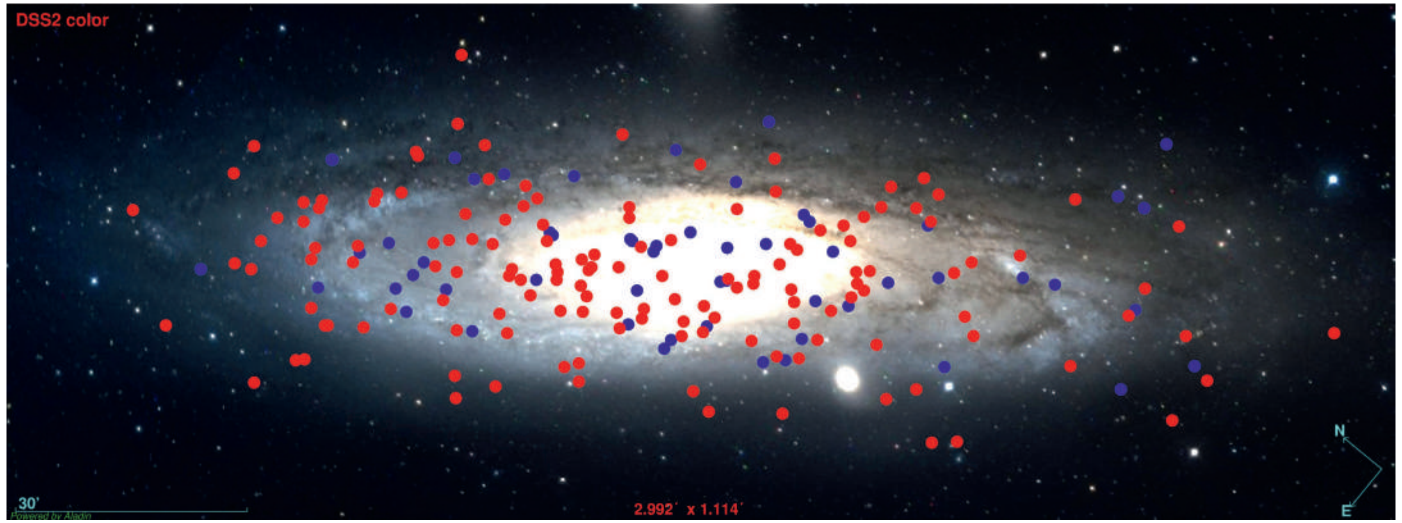
whatever scenario, single- or double-degenerate, leads to the SN explosion. SN Ia are paramount in cosmology because they are the strongest indicator of the existence of dark energy which comprises a large majority of the mass-energy in the Universe. SySt are also very suitable to study nova life cycles, because they have higher accretion rates and shorter recurrence timescales than classical novae with dwarf donors, and therefore their life cycles are much shorter. In addition, their evolved donors are bright in the optical red and near infrared which makes it relatively easy to measure their radial velocities from absorption lines, and to derive reliable masses of the binary components. SySt can be also detected in nearby galaxies and distance-related parameters can be reliably determined.

SySt are very demanding targets to study. Their composition, specifically the presence of evolved RG and its accreting companion, place them among the most variable stars, with time-scales from minutes through to days, years and even many decades. Their orbital and other parameters can be revealed only by patient monitoring of their spectra and light curves over very long periods – a slow science but of long lasting value. Our research is based on multi-frequency observations, involving world-class telescopes, covering the whole spectral range from radio to space UV and X–rays, and different observational techniques (photometry, spectroscopy and various imaging methods). We also participate in some theoretical projects mostly focused on more realistic approaches to mass transfer in SySt, and most recently on modeling the evolution of selected SySt.

One of our main research projects aims at improving the knowledge of binary parameters of SySt. So far, it has resulted in many interesting results, e.g., the first spectroscopic orbits for several Galactic SySt. We have demonstrated that the WD component of the symbiotic recurrent nova RS Oph is indeed very massive and clearly made of CO which makes it a prime candidate to eventually produce a SN Ia via the single-degenerate scenario that can be responsible for up to 20% of all SN Ia. We have also derived the spectroscopic orbit of R Aqr, an old nova and SySt with a Mira-type donor which makes it the only such a system with a known orbit. Our study of light curves has resulted in orbital periods for over 50 SySt which almost doubled the number of SySt with known orbital periods, and more are coming soon. With these results, we already know about 90% of measurable orbital periods and their distribution (which cannot be affected by any selection effects; see Fig. 1) cannot be reproduced by binary evolution models. We have also found that many SySt show ellipsoidal light curves, indicating that the RG is (or very close to) filling its Roche lobe which, combined with the fact that the RG is the more massive component, poses a serious problem for binary evolution theory because such systems are expected to inevitably undergo dynamically unstable mass transfer. At present, we are monitoring radial velocities of Magellanic SySt with SALT that will soon provide the first ever orbits for extragalactic SySt. We also participate in monitoring of some SySt with accreting NSs with Gemini South, aimed at deriving spectroscopic orbits and photospheric abundances.

Another important achievement is the first ever determination of photospheric chemical abundances, CNO, $^{12}C/^{13}C$, and iron peak elements, for over 50 symbiotic RGs. Their metallicity range from [Fe/H] ~ -1 to ~0.6 dex with a median around [Fe/H] ~ -0.2 is consistent with most SySt being members of a disk/thick disk population, and in some cases of an extended thick disk/halo population. We have found that all investigated RGs experienced the first dredge-up as indicated by their enhanced $^{14}$N, depleted $^{12}$C, and decreased $^{12}C/^{13}C$ (Fig. 2). However, the first dredge-up is insufficient to explain the observed very low $^{12}C/^{13}C$. A possible solution to this conundrum is that there is an additional mixing process and/or pollution due to past mass transfer. Recently, we have also found evidence for the s-process enhancement (manifested by strong ZrO) in several Galactic and extragalactic SySt with M-type giants and Li-enhancement in some SySt with K-type giants.

Finally, our ongoing systematic search for SySt in selected regions of Milky Way, the Magellanic Clouds, and the Local Group of Galaxies resulted in the discovery of several dozen Galactic and a few hundred extragalactic SySt including the first SySt in M31 (Fig. 3) and M33. Our discoveries are very important for deriving realistic estimates of SySt total populations in various (e.g. metallicity) environments. The extragalactic SySt are particularly important because of their known distance, and their number already exceeds the number of Galactic SySt with known distances (and distance-related parameters like, e.g., luminosities), which makes them an important benchmark for theoretical predictions.



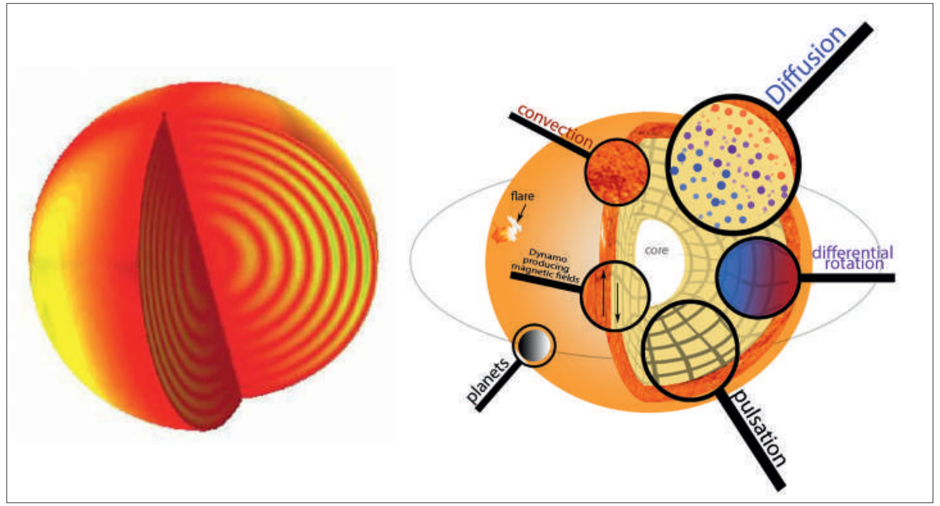
>> Fig. 3: The distribution of M31 SySt (red) and possible SySt (blue) detected by our survey, and overlaid on the DSS2 optical image of M31.
Image credit: K. Iłkiewicz.

**Gerald Handler**

# Asteroseismology – taking the pulse of the stars

The electromagnetic radiation received from the stars is the main source of information astronomers use to study the universe. However, the light of the stars is radiated away from their surfaces, carrying no memory of its origin in the deep interior. Therefore it would seem that there is no way that the analysis of starlight can tell us about the physics going on in the unobservable stellar interiors. Fortunately, there are stars that reveal more about themselves than others.

Variable stars are objects for which one can observe time-dependent light output, on a time scale shorter than that of evolutionary changes. A special subgroup of variable stars are pulsating stars. These objects can change their sizes and shapes as well as temperatures, resulting in periodic net changes in their light output, which can be measured by astrophysicists. Because these oscillations are due to standing waves in the stellar interior, their frequencies carry information about the physical conditions of the regions in which they protrude. That signal can then be inverted to sound the stellar interior. Any correct stellar model must reproduce the observed oscillation frequencies correctly; if not, these frequencies can be used to refine the model. This method is called asteroseismology and has greatly improved our knowledge of stellar interiors over the years. A schematic of stellar oscillations and examples of which physical processes can be studied with them is shown in Fig. 1.



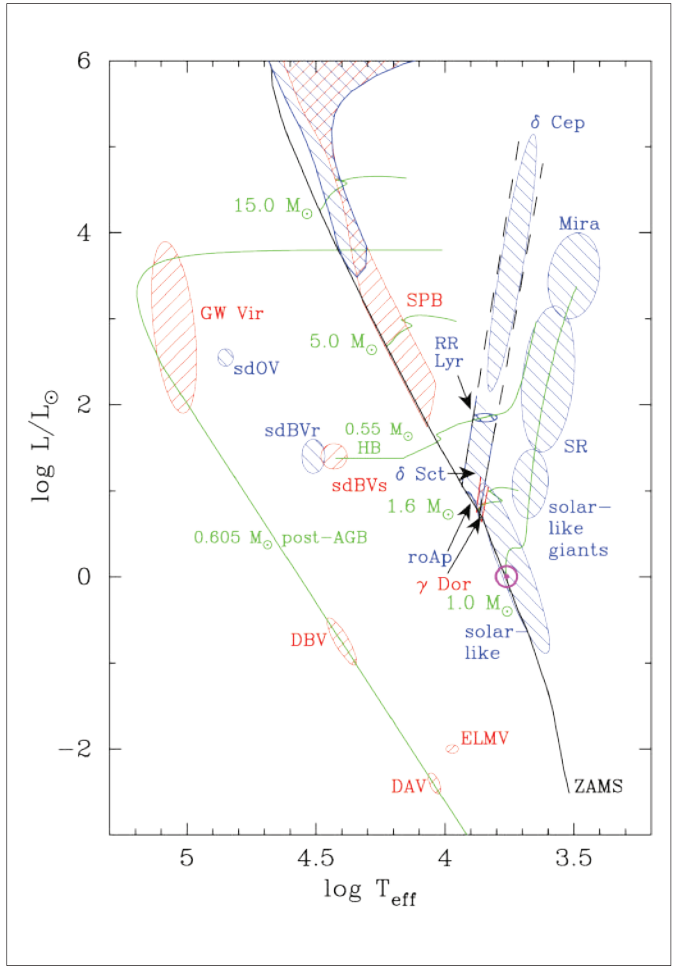
>> Fig. 1: Left: the principle of asteroseismology: standing waves on the stellar surface also protrude into the interior, generating a typical „sound" of a star. Right: Some of the physical processes that can be studied with asteroseismology.
Image credit: V. Antoci

It may seem that asteroseismic methods can be applied to only a small sample of stars. The recent past has shown that just the opposite is the case as more and more classes of pulsating stars have been discovered. Fig. 2 is a schematic Hertzsprung-Russell Diagram showing the location of selected types of pulsating star. It demonstrates that asteroseismology can be applied to stars of virtually all masses and evolutionary stages, and as it will become clear below, researchers at CAMK PAN have made an impact in the study of a large number of those types.

CAMK PAN has been a pioneering institute in asteroseismic studies, most significantly pushed forward by Wojtek Dziembowski, one of the founders of theoretical asteroseismology who published a series of groundbreaking papers mostly in the 1970s. The 1980s saw some applications of the theory to known pulsating stars including our Sun plus theoretical studies of the interaction between different stellar pulsations. The main questions addressed in the 1990s were how stars select the modes in which they oscillate and what excites the pulsations in some types of star, culminating in the discovery of the driving mechanism of Beta Cephei and Slowly Pulsating B stars by Dziembowski and his student at the time, Paweł Moskalik.

In the same decade the asteroseismology group at CAMK PAN was extended with the addition of Alexey Pamyatnykh and collaborations with observers were established. Notably this extended the realm of stars examined to Delta Scuti pulsators, although the main focus was on the Sun. In the first decade of the 2000s, studies branched out even further towards the rapidly oscillating Ap stars, but also to classical pulsators such as Delta Cephei and RR Lyrae stars and techniques of pulsational mode identification.

Whereas the scientific focus of asteroseismology at CAMK PAN has been theory for four decades, the addition of the present author to the institute added an observational theme. The close collaboration between theorists and observers is an asset and provides inspiration for both types of study, and takes advantage of the ever increasing measurement accuracy for stellar oscillations due to projects such as the Kepler and TESS space missions and our very own BRITE. Interpretation of the data is aided by the Warsaw-New Jersey stellar evolution and pulsation code developed at CAMK PAN, but collaboration and integration of this knowledge into modern codes such as MESA is carried out as well.



>> Fig. 2: A schematic Hertzsprung-Russell Diagram with the domains of selected types of pulsating stars indicated. Stars amenable to asteroseismology can be found at all temperatures, masses and evolutionary stages.

In the most recent past, the focus of theoretical asteroseismic studies at CAMK PAN has been on Delta Scuti stars and pulsating red giant stars, but perhaps most particularly on general questions of the excitation of pulsations in stars. Since these are mostly due to opacity effects, this perhaps single most important physical input to stellar structure and evolution codes can be tested, and suggestions be made where improvements are still necessary.

On the observational side, the excellent data of the previously mentioned photometric space missions in combination with ground-based photometric and spectroscopic support observations are being exploited to study Beta Cephei and Delta Scuti pulsators, but also hot white and pre-white dwarf stars and in particular pulsators in binary stars. That the full range of the occurrence and phenomenology of asteroseismic targets is still not recognized even nowadays is proven by the recent discovery of so-called single-sided pulsators, oscillators in close binary systems whose pulsation axes have been pulled into the orbital plane by the tidal forces of their companion star, a finding prominently involving researchers at CAMK PAN.

Team members: Sowgata Chowdhury, Gerald Handler (head), Filiz Kahraman Alicavus, Paulina Sowicka, Elżbieta Zocłońska.

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**Radosław Smolec**

# Classical pulsators research at CAMK PAN

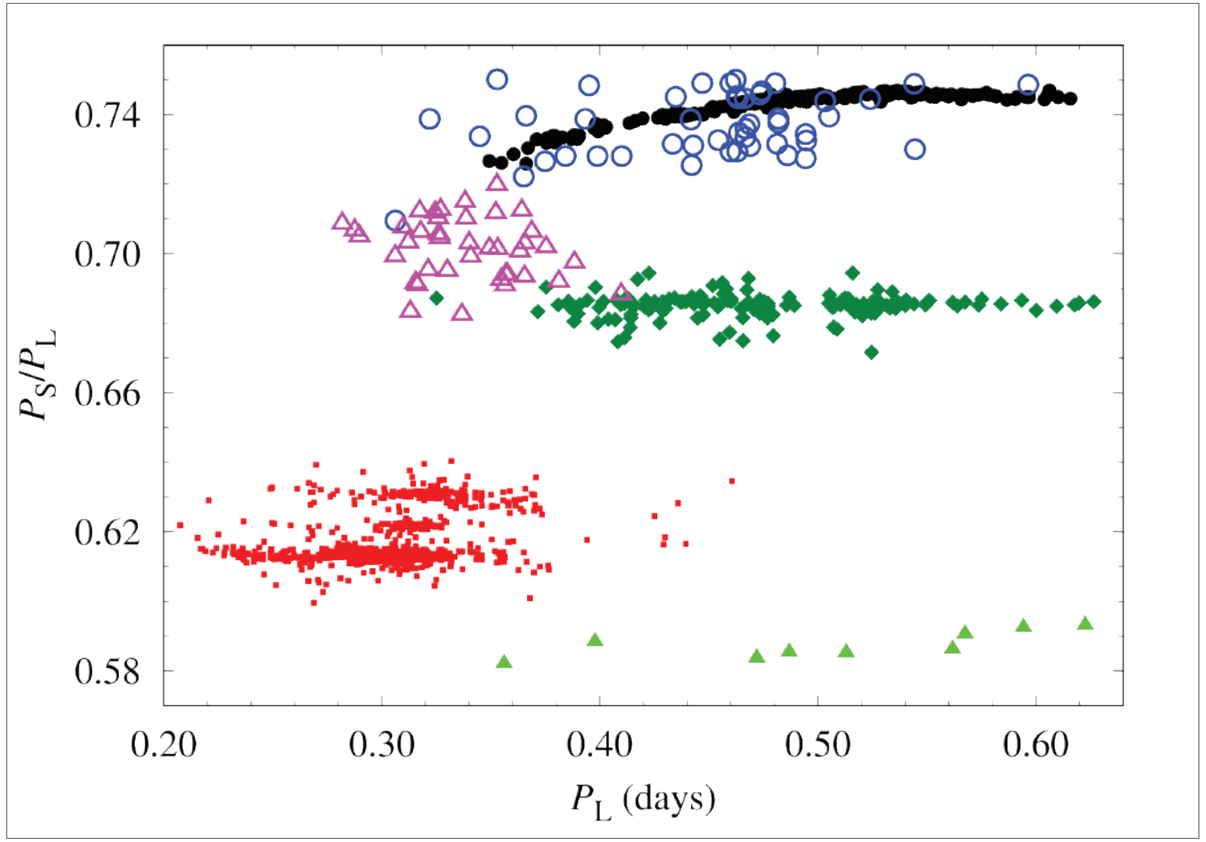
Classical pulsators, Cepheids and RR Lyrae stars, are among the most important tools of modern astrophysics. They are excellent standard candles used to measure distances in the Universe, and for classical Cepheids the famous period-luminosity relation holds, making them a key rung of the cosmic distance ladder.

At our institute classical pulsators are not just tools, but a subject of research. We are interested in the challenges these stars pose to stellar pulsation and evolution theories. In the simplest case the envelope of a pulsating star cyclically expands and then contracts, while its spherical shape is preserved. This is a fundamental mode of pulsation. In the first overtone mode the pulsation period is shorter; we have a nodal surface inside a star, just as we can have a node on a vibrating string, which leads to a higher frequency tone.

Single mode pulsation, although astronomically important, is boring for us: we enjoy two or more pulsation modes excited at the same time, and our stars can indeed pulsate this way! Double-mode radial pulsators, pulsating simultaneously in the fundamental and first overtone modes have been known for years. Using pulsation theory we can predict the periods of the pulsation modes for given stellar parameters (mass, luminosity, temperature and metal content). Already with two pulsation modes, we can estimate the mass and metallicity of a star. To that end we use the Petersen diagram, in which the period ratio of the two modes is plotted versus the longer period. In Fig. 1 we show the Petersen diagram for RR Lyrae stars. The black dots are double-mode stars that pulsate simultaneously in the radial fundamental mode and radial first overtone mode – we call them RRd stars. Pulsation models reveal that RRd stars with short periods and low period ratios must be metal rich, while those with longer periods and high period ratios must be metal deficient and more massive.

In the past, masses of double-mode classical Cepheids estimated from pulsation theory were in strong conflict with masses predicted by stellar evolution theory. This long-standing problem was partially solved when new opacity tables were released and included in the calculations. The discrepancy is still there, at a level of 10 to 20%, but today we know that pulsation theory is right! We learned that when our colleagues from the Araucaria team precisely weighted and determined other physical parameters for a classical Cepheid in an eclipsing binary system. These parameters, when inserted into pulsation codes, yield a pulsation period nicely matching the observed one. Investigating the cause of the remaining mass discrepancy is among our goals for the future. We hope that new PhD students in our group, Rajeev Singh Rathour and Oliwia Ziółkowska, will make significant contributions to this and other Cepheid puzzles.

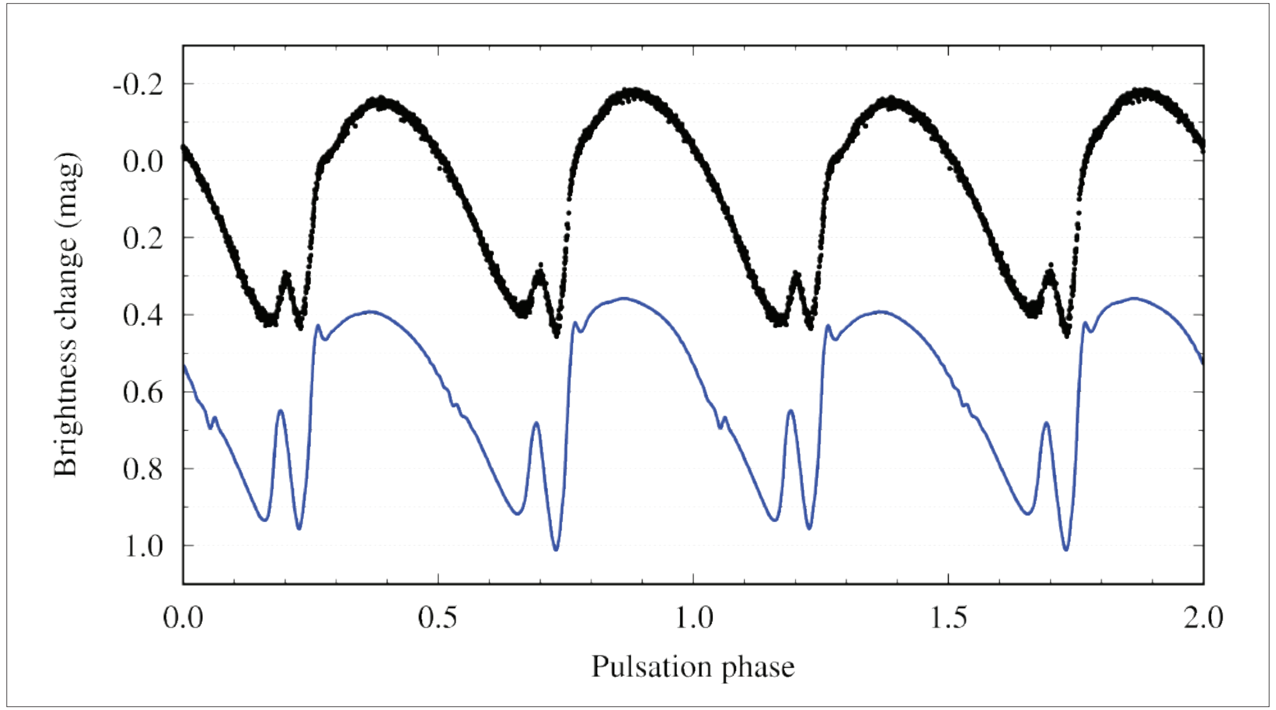
The Petersen diagram in Fig. 1 is full of double-periodic stars that seem to form distinct groups. Not all of them are RRd stars however. In fact, in the majority of these stars, we observe radial first overtone mode and other low-amplitude periodicity, that cannot be linked to radial pulsation. Most likely these additional periodicities correspond to non-radial pulsations – a cyclic variability during which the spherical shape of the star is deformed. Classical pulsators are no longer simple,



>> Fig. 1: The Petersen diagram – a plot of shorter to longer period ratio, $P_S/P_L$, versus longer period, $P_L$, for RR Lyrae stars. RRd stars are marked with black dots. Other classes of double-periodic RR Lyrae stars are marked with different symbols. Our group contributed to the discovery and study of the majority of stars plotted in the diagram.

textbook examples of radial stellar pulsation – they turn out to be much more complex systems. Our group has contributed a lot to the discovery and study of new forms of pulsation, but the field is far from being entirely explored. We still have little idea what is causing the additional variability in double-periodic stars marked with green diamonds in Fig. 1. The group was discovered by Henryka Netzel – a PhD student in our group, who also discovered hundreds of other double-periodic RR Lyrae stars plotted in Fig. 1. The stars marked with small red squares are particularly interesting. An analogous group of double-periodic pulsators exists among classical Cepheids. A world-renown expert on pulsating stars, our mentor and colleague Wojtek Dziembowski proposed that additional periodicities are due to the presence of non-radial pulsations of a specific geometry. With this knowledge at hand, we hope to learn something interesting about these stars soon.

Yet another intriguing phenomenon observed in classical pulsators is periodic modulation of pulsation. In RR Lyrae stars the effect has been known for more than a hundred years – it is called the Blazhko effect. While it seems that we are closer and closer to revealing the cause of the Blazhko effect, the final step is still to be made. At the same time new puzzles continue to emerge. Our group discovered periodic modulation of pulsation in tens of classical Cepheids, including double-mode ones, and in type II Cepheids. One of the most intriguing discoveries is a mean brightness modulation of classical Cepheids, the most important standard candles. Fortunately the effect is of very low amplitude and averages out in typical observing series. The standard candles are safe, but certainly more puzzling than before. What causes these modulations?



>> Fig. 2: Black dots show the light curve for OGLE-T2CEP-BLG-279 – the first BL Her star with period doubling effect. Note the subtle differences at brightness maxima and minima for the two consecutive pulsation cycles. Blue line corresponds to nonlinear pulsation model showing the period doubling effect, computed with Radial Stellar Pulsations (RSP) tool implemented in MESA.

To address the problems of stellar pulsation theory we need state-of-the art tools. Our group has a long-standing experience in modeling stellar pulsations. The linear pulsation codes of Wojtek Dziembowski are among the most efficient and precise in the world. However, non-linear codes are needed to predict the shapes of light curves and study interactions between pulsation modes. Using such codes, Paweł Moskalik of CAMK PAN and Robert Buchler, predicted in 1992 that BL Her stars, a subgroup of type II Cepheids, should show a period doubling effect: alternating deep and shallow brightness maxima and minima. Twenty years later the effect was indeed discovered – what an impressive proof of the predictive power of stellar pulsation theory! This interesting light curve is shown in Fig. 2 along with a pulsation model computed with the non-linear convective code developed by me as part of my PhD thesis. Recently, this code was included as a new software instrument (Radial Stellar Pulsations, RSP) in the *Modules for Experiments in Stellar Astrophysics* (MESA) package, and is publicly available.

**Michał Różyczka**

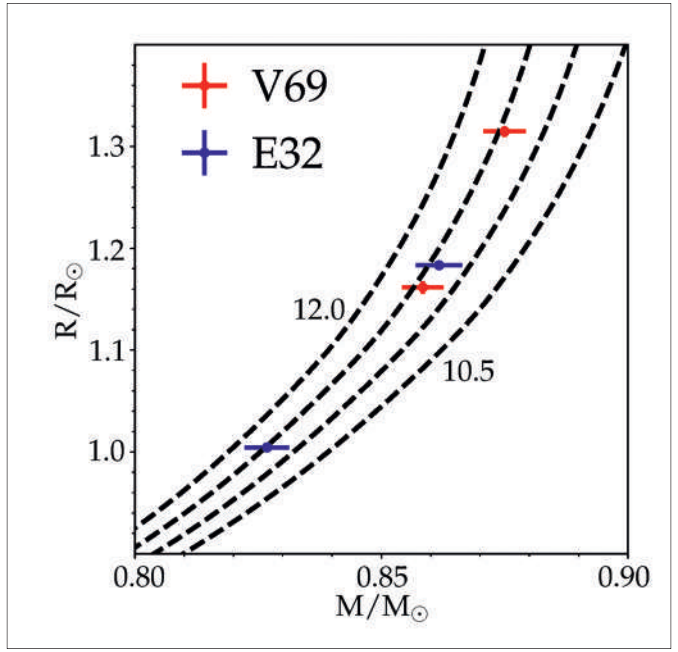
# Mining the globular clusters

Our Galaxy, the Milky Way, is accompanied by nearly 200 globular clusters – almost spherical stellar aggregates comprising up to over one million members. They are a real treasure trove from which astronomers extract data about the Galaxy's early history, chemical evolution, and dynamics. They are also a unique laboratory where the theory of stellar evolution can be thoroughly tested.

Our institute runs a program CASE (Clusters AgeS Experiment), initiated by Prof. Janusz Kałużny with the goal of determining ages and distances of globular clusters. To that end, light and velocity curves of detached eclipsing binaries (DEBs) belonging to the clusters are analyzed. The analysis yields masses, radii and luminosities of the components of a DEB. Given the mass ***M***, the theory predicts how the radius ***R*** of a star changes with time, thus turning it into an age indicator (see Fig. 1). The distance of a star, in turn, can be derived from its luminosity and apparent magnitude.

Our sample comprises the ten globular clusters nearest to the Sun. Using the facilities of the Las Campanas Observatory (LCO) we have collected over 50000 CCD frames from the 2.5-m du Pont telescope, over 75000 frames from the 1-m Swope telescope, and over 1000 spectra taken on the Magellan Clay telescope at LCO, and the VLT telescope at the European Southern Observatory. We have discovered over 600 cluster variables, and among them nearly 80 DEBs. The 16 DEBs most suitable for our purposes have been analyzed, and another four are being processed.

While cluster ages in excess of 15 gigayears (Gyr) were quoted still in 2001, the universe was already known to be younger than 14 Gyr. In 2002 CASE helped to remove this discrepancy thanks to a pioneering age analysis of a cluster DEB, which yielded a value of 11.6±0.6 Gyr. The cluster was ω Centauri.



>> Fig. 1: A recent determination of the age of the globular cluster 47 Tucanae. E32 and V69 are DEBs belonging to the cluster. Masses and radii of their components in solar units can be read off from horizontal and vertical axis, respectively. The lines are theoretical isochrones showing the expected locations of same-age stars. The isochrones are spaced by 0.5 Gyr from 10.5 to12.0 Gyr.
Image credit: CASE, A. Dotter (CfA).

Compared to the Sun, stars in globular clusters contain much less elements heavier than helium (astronomers say they are "metal-poor"). For a long time the theoretical models of such objects could not have been tested due to the lack of observational data. Another pioneering CASE analysis yielded masses and radii of metal-poor stars with an accuracy better than 1%. The stars were the components of a DEB in the globular cluster 47 Tucanae. Simultaneously, the age of the cluster was found to be 11.2±0.2 Gyr.

Globular clusters contain blue stragglers – stars which seem to be much younger than the main cluster population. They are supposed to be products of stellar collisions or mass exchange between DEB components. We proved that the second possibility is indeed realized. While analyzing a DEB in the globular cluster M55 we found it to be a blue straggler "in the making". In this binary system one of the components continuously "siphons" mass from its companion, which makes it not really younger, but "rejuvenated". The mass transfer causes the orbital period of the binary to increase, doubling it in just $10^6$ years (which is extremely fast in astronomy).

Based on the analysis of three DEBs in the globular cluster M4 we concluded that theoretical models of the evolution of metal-poor stars are reliable up to the moment when the principal stellar fuel – hydrogen – is exhausted in their cores. The overall correctness of the theory implied another, quite exciting conclusion concerning the globular cluster NGC 6362, in which we analyzed two DEBS: we found one of them to be 1.3±0.4 Gyr younger than the other. While independent indications of age spread among cluster members are known, our result, if confirmed, will be the first direct detection of such a non-coevality.

Stars in globular clusters are in a permanent motion, resembling bees in a beehive. An observer on the Earth sees this as minuscule shifts of their positions on the sky – the so-called "proper motions". Measuring proper motions allows to distinguish between real cluster members and stars which accidentally appear in the observed field of the sky. As a by-product of CASE, we compiled catalogs of proper motions in cluster fields derived from du Pont data for about 90000 stars, and from Swope data for about 500000 stars. Their accuracy rivals that achieved by the *Gaia* satellite in its 2$^{nd}$ data release.

To introduce further CASE findings to laymen we would have to indulge in lengthy explanations for which there is no space in this book. However, professional astronomers may find it interesting that contact systems of W UMa type are found in globular clusters exclusively in the vicinity of the main sequence turnoff. We detect them only down to ~1 mag below the turnoff, although we identify other type variables by 2 – 3 mag weaker. This suggests that – at least in the clusters – such systems are brought into contact due to effects of nuclear evolution rather than magnetic braking. Finally, it is worth mentioning that we have found a few eccentric binaries which should have been circularized long ago. They are a clear evidence of relatively recent close encounters between cluster members.

>> Fig. 2: The Globular Cluster M12. Photograph taken with the Swope telescope at Las Campanas Observatory.
Image credit: A. Olech.

**Mirosław Giersz**

# Dynamical evolution of large stellar clusters

Star clusters are natural laboratories for studying stellar dynamics, star formation processes and physical nature of "exotic" objects. They are also a formidable test range for stellar evolution theory and population synthesis methods – the foundations of our understanding of structure formation in the Universe.

The study of dense, gravitationally bound clusters of stars, open clusters (OC), globular clusters (GC) and nuclear star clusters (NSC), is one of the most interesting subjects of observational, theoretical, and computational astronomy. GCs can be used to "weigh" our Galaxy, to probe the structure of its dark matter halo, and to impose restrictions on the theories of galaxy formation. Studying OCs and GCs makes it possible to put stricter constraints on theories of star and star cluster formation by examining the influence of such factors as primordial mass segregation or removal of residual gas left after the star formation period. Studying NSCs, in turn, allows to uncover processes leading to the formation of supermassive black holes (SMBH).

The last decades have brought an enormous amount of very detailed observational data that has dramatically increased our knowledge about star clusters. Unfortunately, theoretical studies cannot yet match observational achievements. The MOCCA group originated at CAMK PAN with the aim to reduce the gap between observations and advanced dynamical simulations. A wide range of topics related to the evolution of star clusters required us to first understand the physical processes governing the evolution of star systems, then to create appropriate research tools, and finally to compile an appropriate database for statistical comparisons of simulation results with observations.

We employ our own computer code Mocca (MOnte Carlo Cluster simulAtor) which accounts for the most important processes driving the evolution of star clusters, e.g. evolution of single stars and binary systems, formation of multiple subpopulations, residual gas removal, or escape of stars from clusters tidally limited by the parent galaxy. Strong dynamical interactions between binary systems and single stars are handled by the Fewbody code including dissipative processes due to tidal forces, and gravitational wave radiation. Mocca allows us to track the evolution of star clusters from their birth to death, providing information about individual stars, binary systems and other objects at a level of detail comparable to direct N-body codes, but incomparably more efficiently in terms of CPU time. Currently, the Mocca Survey Database contains about three thousand evolutionary models of star clusters stored on the Mocca Server at https://moccacode.net/, and is freely available for all interested researchers. Our simulations provided many interesting results about blue straggler stars (BSS), cataclysmic variables (CVs), black hole (BH) mergers, formation of intermediate mass black holes (IMBHs), and evolution and dispersion of clusters harbouring a black hole subsystem (BHS).

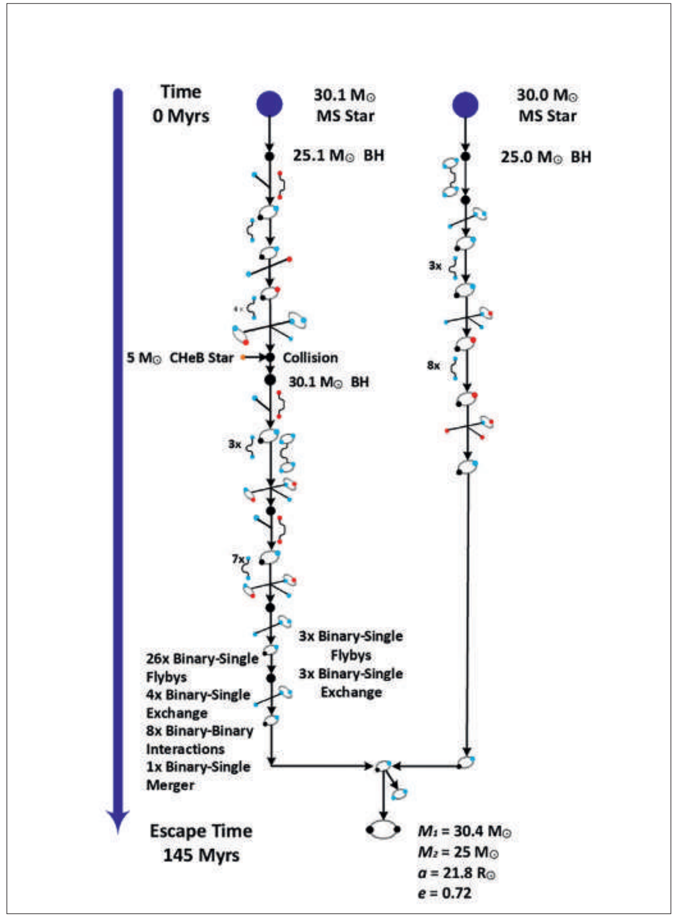
Work related to CVs brought significant refinements of the theory describing the parameters of primordial binaries. We also demonstrated that – contrary to widespread expectations – dynamical interactions are not the main channel of CV formation in globular clusters. According to our results, the factors mainly responsible for the observed properties of these objects are stellar evolution, dissolution of primordial binaries in dynamical interactions, and mass segregation in clusters.

Studies related to BH dynamics have shown that BH mergers within GCs can significantly contribute to the observed frequency of these spectacular events (see Fig. 1 for a typical sequence of interactions leading to a BH-BH merger in a globular cluster).

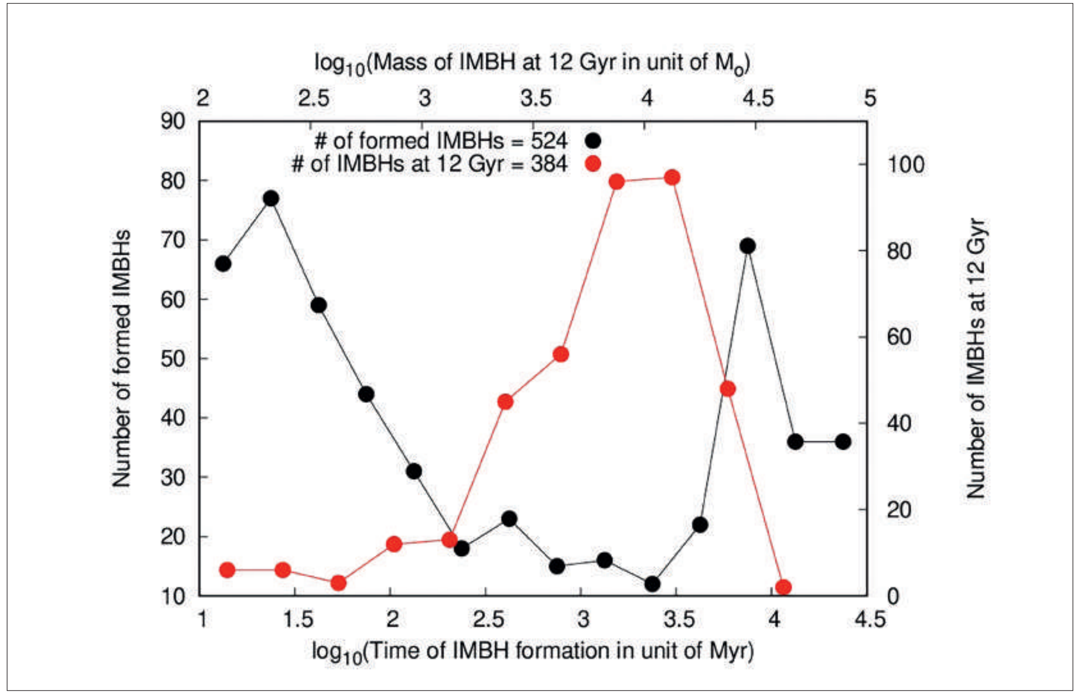
Depending on the total mass and initial mass function of a GC, over a thousand of BHs may form in it during its lifetime. While some of them are ejected from the cluster as a result of supernova explosions or dynamical interactions, some remain in the cluster and can form the so-called BHS. The Mocca Database revealed a close correlation between the number density of BHs and observational parameters of clusters. Using this correlation, we identified the 29 Galactic GCs most likely to contain BHS. For several of them the same conclusion was reached by other authors based on theoretical considerations or observations.

When analysing the Mocca Survey Database in the BHS project, we noticed that some cluster models disperse very rapidly, while others, differing only by a higher BH natal kick velocity during the supernova explosion, evolve very slowly. We identified a new dispersion mechanism occurring in tidally filling clusters which maintain a BHS until the end of their evolution. The cluster disperses extremely rapidly, but only when its mass falls below about 20% of the initial mass. The driving agent is a positive feedback between the rate of energy transfer from BHs to stars, and the escape rate of stars, which in turn reduces the escape velocity from the cluster. At some point, the escape rate is so large that the cluster is unable to maintain the dynamical balance and disperses on a dynamical time scale.

We also proposed a new mechanism of IMBH formation, essence of which is the progressive buildup of BH mass due to strong dynamical interactions, and mass transfer in binary systems. This can proceed along two different branches (FAST or SLOW; see Fig. 2). The first case refers to clusters with an initial density above $10^7\,M_\odot/pc^3$, in which frequent collisions between main sequence stars lead to a very rapid (on a scale of several million years) formation of an extremely massive star (with a mass of



>> Fig. 1: A typical sequence of interactions in a globular cluster leading to a BH-BH merger. During the initial evolution of the cluster dozens of binary-single and binary-binary flybys, several binary exchanges, and a few mergers and collisions occur. Such a picture is not an exception, but rather a norm in dense stellar environments. The intracluster dynamics can enforce the merger of objects which would never merge without its influence.



>> Fig. 2: Bottom and left axes – histogram of IMBH formation times in Myr (black). By assumption, an IMBH is formed when its mass exceeds 150 solar masses. Top and right axes – histogram of IMBH masses at 12 Gyr (red). Logarithmic bins are 0.25 wide for both the histograms.

hundreds of M$_\odot$). The star then collides with a stellar mass BH, and forms an IMBH. In originally less dense clusters undergoing core collapse (at a density of about $10^5$ M$_\odot$/pc$^3$ and age of about 1 Gyr) stellar mass BHs collide or merge in binaries. Further interactions in binary systems, and collisions (mainly with main sequence stars), eventually lead to the formation of an IMBH.

The SLOW channel is a highly stochastic process, which implies that clusters with identical initial parameters may or may not form an IMBH, and that there is no simple correlation between initial conditions and observational parameters of GCs containing an IMBH. However, for both the channels we observe that the higher the density of the cluster, the faster and easier it is to form more massive IMBH.

Another interesting result of our simulations concerns the "dynamical clock", which, based on the spatial distribution of BSSs, was supposed to indicate the dynamical status of the cluster. BSSs are stars more massive than the main sequence stars, and, due to mass segregation, they should sink more quickly to the center of the cluster. The hand of the dynamical clock was defined as the avoidance radius at which the BSS distribution has a minimum. We showed that this radius may vary rapidly, and its measurement in real clusters is highly unreliable.

These are only a few examples of the results based on the Mocca Survey Database. If you intend to analyse the Database or run Mocca simulations, please contact us and we will provide any information you need.

Mocca team members: Abbas Askar, Diogo Belloni, Mirosław Giersz (head), Douglas Heggie, Arkadiusz Hypki, Agostino Leveque and Rainer Spurzem.

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### Ewa L. Łokas

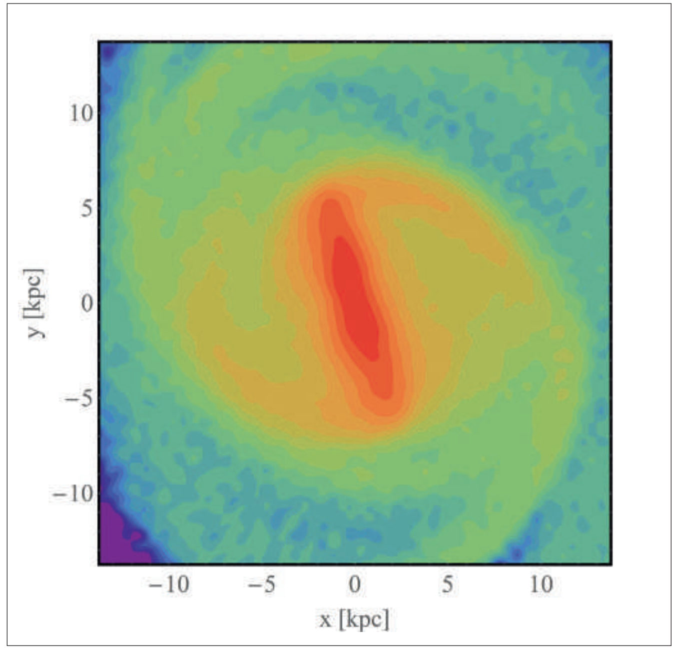
# Mysteries of barred galaxies

Barred galaxies comprise a significant fraction of spiral or late-type galaxies in the Universe. Our Galaxy, the Milky Way, also contains a bar. The formation and evolution of bars is a subject of intensive study both via theory and observations.

Bars can be studied theoretically mainly via N-body and hydrodynamical simulations. In such simulations a large number of massive particles corresponding to stars, gas and dark matter is followed by solving equations of gravity and hydrodynamics. We have known for decades that an isolated, gravitationally bound system composed of a thin disk embedded in a dark matter halo is subject to the bar instability. The instability results in the formation of an elongated structure in the inner part of the disk with stars on radial, rather than circular orbits. Although the process depends on many parameters and can occur on different timescales, it seems to be quite common and results in the formation of bars quite similar to those observed.

Bars can also form in galaxies as a result of interactions with other objects. A disky dwarf galaxy orbiting the Milky Way, a normal-size galaxy orbiting a cluster, or a galaxy flying by another object of similar size, all experience tidal forces from their neighbor, similar in nature to those causing sea tides on the Earth resulting from the gravity of the Moon. During such an encounter, tidal forces from the perturber temporarily distort the orbits of stars in the galaxy, igniting the bar instability. The closer the encounter, the stronger the interaction is and the more pronounced the resulting bar.

Recently, using N-body simulations we studied fly-by interactions of two identical galaxies similar to the Milky Way, initially composed of disks embedded in dark matter haloes that were stable against bar formation in isolation. The galaxies were placed on orbits of different parameters resulting in different tidal forces experienced. We found that the formation of a tidally induced bars depends critically on the orientation of the galaxy's internal angular momentum with respect to its orbital angular momentum. The bars form only in galaxies on



>> Fig. 1: Surface density distribution of stars in a simulated galaxy seen face-on. A tidally induced bar resulted from a prograde fly-by interaction with another similar galaxy.

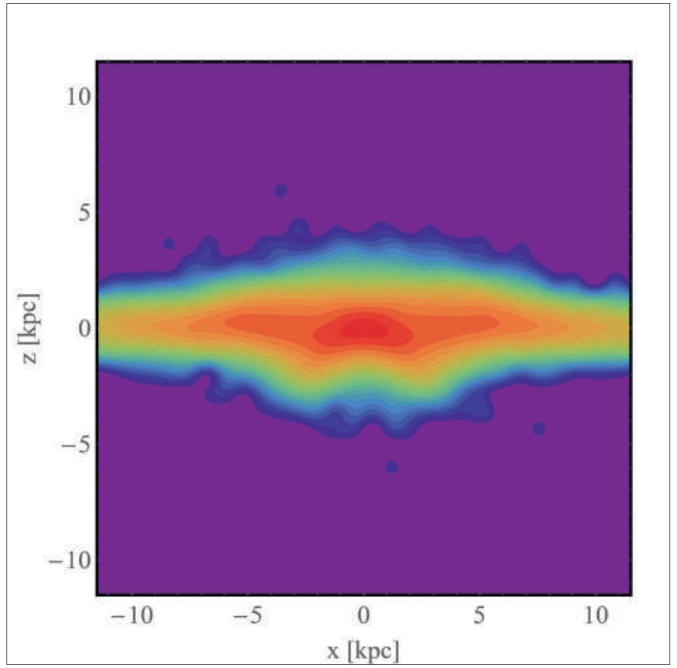
prograde orbits, that is such that have the two momenta pointing in the same direction. The reason behind this dependence is the fact that in such a configuration the stars in the galaxy are subject to the tidal forces for a longer time than in the case of retrograde (opposite) orientation of the momenta. We also confirmed this scenario in the cosmological context using the Illustris simulations.

Almost all strong simulated bars, independently of their origin, undergo a period of violent buckling instability. The phenomenon involves strong distortions of the bar in the vertical direction, out of the disk plane, and is probably caused by vertical resonances of stellar orbits. The orbits of stars in the bar are significantly changed during this time leading to the formation of a pronounced boxy/peanut shape visible in the edge-on projection. Such a shape is observed in many real galaxies, including the Milky Way.

We studied the buckling phenomenon in a Milky Way-like galaxy using N-body simulations and identified a few stages of the process. It starts with a small smile- or frown-like distortion of the bar which is probably due to banana-like stellar orbits. This distortion then winds up due to the rotation of the galaxy and disappears leaving behind the bar significantly thickened and weakened. Later on, a similar phenomenon can reappear in the outer part of the bar. This second phase of buckling lasts longer and extends the boxy/peanut shape to larger radii.

If the galaxy contains a significant fraction of its baryonic component in the form of hydrogen and helium gas, the bar forming in the disk is in general weaker, although the presence of the gas can speed up bar formation due to the density fluctuations in the gas. The bar forms both in the stellar and gaseous component, but the one in the gas is less pronounced and dissolves on the time scale of a few gigayears. The buckling of the stellar component is also significantly weaker in gas-rich galaxies, and if the gas fraction is high enough it may not occur at all. Still, the boxy/peanut shape can form in such galaxies, in the stellar as well as the gas component.

The process of the formation of galactic bars, as well as the phenomenon of buckling instability, still contain a few puzzles and thus deserve further study. It remains to be investigated how frequently the bars are tidally induced in the Universe in comparison to their formation in isolation. The nature of the buckling instability is still controversial, it is not clear whether it is related to the vertical resonances of stellar orbits or rather to some kind of fire-hose instability, in which case it would be triggered by a low enough ratio of the vertical to the radial velocity dispersion of the stars in the bar. The stellar orbits after the bar buckling reveal a very tight relation between their vertical and circular frequencies which also remains to be explained.



>> Fig. 2: Surface density distribution of stars in an edge-on view during the first buckling phase of a simulated galaxy evolving in isolation. The distortions of the bar in the vertical direction, out of the disk plane, are clearly visible.

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**Ivana Ebrová**

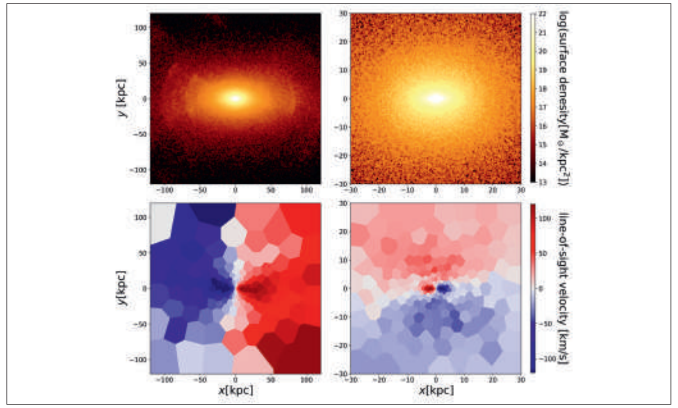
# The hidden charm of elliptical galaxies

At first sight, elliptical galaxies may seem bland and uninteresting, with their oval shape and smooth brightness profile. Deeper photometric observations uncover a rich world of substructures such as stellar streams and shells, the footprints of past galactic mergers. Spatially resolved spectroscopy adds a whole new dimension of data to explore.

A convenient tool to explore what the observed features can tell us about the nature and evolution of the galaxy is provided by the publicly available data of large-scale cosmological simulations such as the Illustris project, where the coevolution of dark and baryonic matter is followed from the early universe down to redshift zero. Such simulations have only a limited resolution for each individual galaxy but they provide a huge set of diverse simulated galaxies, evolved in a cosmological context with 3D information including dark matter and full history.

We used Illustris to study galaxies with prolate rotation. Although elliptical galaxies do not rotate as prominently as disk galaxies do, most of them display a clear net rotation. Usually, they rotate as if they were puffed up disks, i.e. they appear to be rotating around the short axis of their elliptical body. However, some galaxies, so-called prolate rotators, appear to be rotating around the long axis. We identified several tens of galaxies with well-established prolate rotation in Illustris. For the vast majority of cases, we traced the origin of this type rotation to a significant merger event in the history of the galaxy. The mergers cover a wide range of initial conditions but the trajectories tend to be rather radial and mass ratios rather high, and they occur at more recent times than mergers that occurred in other galaxies in the simulation. Contrary to previous belief, about half of the prolate rotators in Illustris were created during gas-rich mergers. The stars formed from this gas mostly reinforce the prolate rotation.

In an ongoing project, we employ Illustris data in order to comprehend the kinematically decoupled cores (KDCs) in elliptical galaxies - a topic that proves to be even more challenging. KDCs frequently occur in nature but they are not yet fully understood. In the simulation, some of the KDCs originate in mergers, similarly to the prolate rotation; some are created from stars born after the merger; and some reside in galaxies that did not suffer any significant merger at all.



>> Fig. 1: Examples of two galaxies from the Illustris simulation. Top row: surface density (equivalent of an optical image); bottom row: line-of-sight kinematics. Left: an elliptical galaxy with stellar shells and regular rotation; right: an elliptical galaxy with prolate rotation and a kinematically decoupled core – both features are clearly visible in the kinematic map.

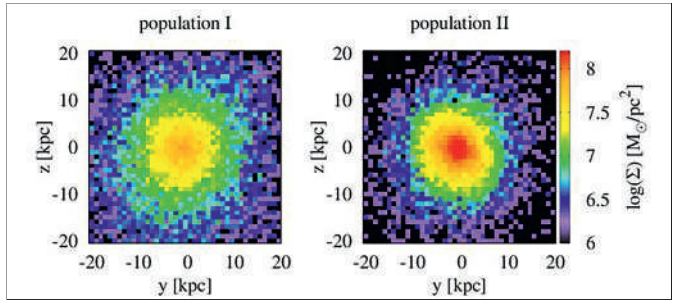
**Klaudia Kowalczyk**

# A deeper look into dwarf galaxies

Astronomical studies have unavoidably struggled with a limited access to the data. We can precisely measure the positions of the stars in the sky but the distances are reserved only for the closest ones. The situation is the opposite when we want to know the velocity of a given star.

For those stars bright enough for spectroscopic observations we can obtain the velocity towards/from the observer, so called line-of-sight velocity from the Doppler effect. On the other hand the transverse movement depends on the change of position and therefore requires extremely accurate astrometry and/or a long time base of observations.

Current samples of line-of-sight velocities for galaxies in the vicinity of the Milky Way never exceed a few thousand measurements. Fortunately, theoretical models allow us to fill some of the gaps. Based on the well established laws of kinematics and dynamics we recreate an object so that for a distant observer its characteristics are the same. One of the methods used to model the data is the Schwarzschild orbit superposition where a galaxy is 'built' by assigning mass to a finite number of orbits available to stars in an assumed total (stars and dark matter) mass distribution.



>> Fig. 1: Comparison of the surface density distribution for two stellar populations of a galaxy from the Illustris simulation.

Over the past few years we have performed a series of tests on simulated data which have shown that the method can indeed supply us with good estimates of the otherwise unavailable parameters: averaged transverse velocities of stars and the dark matter content. The only natural following question was: could we do any better?

A possible extension of our method arises when considering two stellar populations. Although, most of the dwarf galaxies contain little to no gas, they exhibit multiple or prolonged star formation episodes, often triggered by an encounter with another galaxy. Stars born at different stages of galactic evolution are distributed differently and may move on different types of orbits.

Nevertheless, different populations are part of the same object and they feel the same gravitational potential which is generated by all matter in the galaxy. In order to determine whether our results would improve, we applied our method to another set of artificial observations. We modeled the same sample twice, once using all stars as before, and then again studying each population separately and combining the outcomes. We have found that with two populations we recover the same set of best parameters but the accuracy of the result, often referred to in terms of confidence levels, is significantly increased. An application of the revised method to the real data remains as a task for the near future.

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**Grzegorz Pietrzyński**

# Twenty years of precision measuring of the Universe

From ancient observations to present day astrophysics, distance determination has been one of the most important, fascinating and challenging goals in astronomy. Knowing distances is much more than just knowing the scale; it also means knowing the physical nature of the objects in the universe, and each significant improvement in the accuracy of the distance scale has traditionally opened new fields of astrophysical research.

Distance determinations to galaxies allowed to discover the expansion of the Universe, which was one of the most important discoveries in astrophysics. Since then lack of precise and accurate distances to galaxies, which provide the basis for the determination of the famous Hubble constant ($H_0$) describing the expansion rate of the Universe, became a central problem in astrophysics.

After the detection of the accelerated expansion of the Universe (Nobel prize 2011) and the introduction of an enigmatic "dark energy" component of the matter-energy content of the Universe the physical explanation of the nature of dark energy has become a major challenge for astronomers and physicists. The recent empirical determinations of $H_0$ complicated even more our understanding of the Universe. The to-date most precise empirical determination of $H_0$ of 74.03 ± 1.42 km/s/Mpc based on Cepheids and SN Ia differs by about 4σ from the value of 66.93 ± 0.62

>> Fig. 1: Araucaria trees in front of Conguillo lake and volcano Llaima in southern Chile, where our project was originally initiated. We adopted the name Araucaria for the project after the name of these majestic trees, visited frequently by our group members during our frequent hikes in the southern Andes.

km/s/Mpc predicted based on the ΛCDM model and Planck CMB data. This discrepancy, often called a crisis, seems to provide evidence that new physics beyond the standard cosmological model might be required to reconcile different determinations of $H_0$. A significant improvement in the accuracy of the measurement of $H_0$ from the classical (Cepheid-SN Ia) method is therefore of paramount importance for deciding if the current apparent discrepancy with the Planck $H_0$ value does indeed exist, which would be central for cosmology in general, and for truly significant progress towards the understanding of the dark energy phenomenon.

After about 100 years of intensive work on the empirical determination of the Hubble constant, it is evident that any significant reduction of its uncertainty can now only be achieved by improving the accuracy of the absolute calibration of the Cepheids and SN Ia which constitute the largest contribution to the total error budget of the $H_0$ determination.

With this motivation in mind, in 1999 we started on a long term enterprise called the Araucaria Project (see Fig. 1, and https://araucaria.camk.edu.pl) with the main goal of investigating in detail the two most important problems still preventing precise and accurate calibration of the extragalactic distance scale, and, as a result, the determination of $H_0$ with a precision required by modern physics and cosmology: environmental dependencies of the distance indicators and absolute calibration of the whole extragalactic distance scale. In order to achieve this goal we selected a sample of some 30 nearby galaxies (see Fig. 2) hosting rich populations of various distance indicators (e.g. Cepheids, eclipsing binaries, blue supergiants, RR Lyrae stars, red clump giants, stars at the tip of the red giant branch (TRGB), etc …), and applied several different techniques to determine distances to these galaxies. We have been very successful in telescope time applications, and obtained some 2000 observing nights with a wide range of the best telescopes and instruments in the world and in space. Based on this high quality data and on the new tools developed by our group members, our pioneering research often resulted in very significant revisions and improvements of several techniques for distance determination. Relative distances of objects located in very different galaxies allowed us to verify how the brightness of major distance indicators depends on environmental properties like metallicity, extinction, etc.

>> Fig. 2: The spiral galaxy NGC 300 – one of our target galaxies in the Araucaria Project seen in front of at least 100 000 much more distant galaxies. This amazing image published by ESO (https://www.eso.org/public/news/eso0221) was made from 278 images obtained by the Araucaria group with the Wide Field Imager, 67-million pixel digital camera, at 2.2 m MPG/ESO telescope at La Silla, Chile.
Image credit: ESO

We also provided a genuine breakthrough in the absolute calibration of the extragalactic distance scale based on binary systems. Eclipsing binary systems have been considered as an excellent distance indicators for more than 100 years. With current observational facilities, and applying an appropriate surface brightness-color relation (SBCR), the eclipsing binaries have the potential to yield the most direct (one step), and the most accurate (about 1%) distance to nearby galaxies. Indeed the distances to individual systems can be obtained from the simple equation $d\,[pc] = 9.2984 \times R\,[R_\odot] / f\,[mas]$.

The linear radii of the components of the binary systems come from the standard, well known modeling of radial velocities and photometric light curves, while the angular diameters – from the SBCR. The surface brightness is defined as

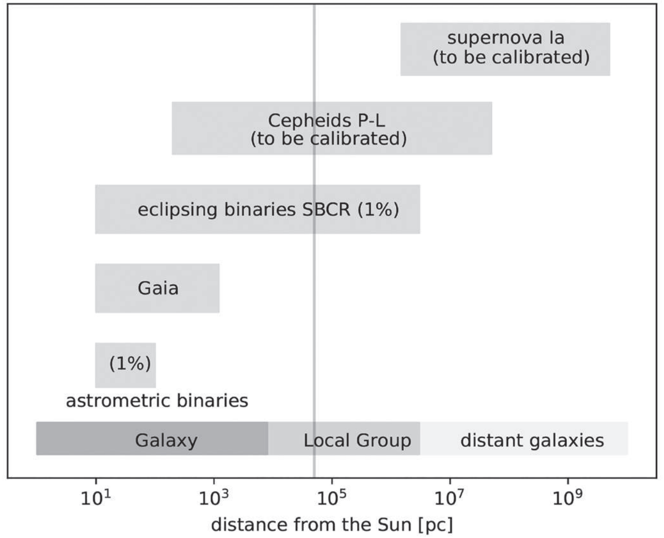
$S_V = V_0 + 5 \times log(\phi)$,

where $V_0$ is the $V$-band magnitude corrected for the reddening, and $\phi$ is the stellar angular diameter. After over 10 years of hard work our group managed to precisely calibrate this technique and applied it to measure the distance to the Large Magellanic Cloud with an unprecedented precision and accuracy of about 1%. Fig. 3 presents an artistic vision of this discovery.

>> Fig. 3: An artistic view of the very precise and accurate distance determination to our closest neighbor galaxy – the Large Magellanic Cloud.
Image credit: J. Bogucki.

The LMC, our closest neighbor galaxy which can be appreciated in the southern sky with the naked eye, is a perfect laboratory to study many different objects and processes, so a precise geometrical distance to this galaxy is extremely important for many different fields of modern astrophysics. Since distances to other galaxies as measured with standard candles (e. g. Cepheids) are in fact derived with respect to the LMC, the distance to this galaxy is also a benchmark for the whole extragalactic distance scale. For this reason, more than 600 distance determinations to the LMC can be found in the literature. However their relatively low precision and lack of control on systematic errors prevent the use of the LMC distance to significantly improve the determination of $H_0$. Our ultra precise LMC distance measurement changed this situation and allowed to significantly improve the absolute calibration of Cepheids and TRGB, which in turn allowed to improve the absolute calibration of the SN Ia, and as the result the determination of the Hubble constant with a precision of about 2%.

One very important aspect of determining truly accurate distances is to understand the physics behind the applied methods. Indeed, we cannot rely on stars whose evolution is incompletely understood to anchor their distance scale to a level of one or two per cent. In particular, given the enormous importance of Cepheids for the determination of the cosmic distance scale and cosmological parameters, it is of great importance to fully understand these stars astrophysically. In this context, Cepheids present a problem which surfaced when it became possible for the first time to apply both stellar evolution and stellar pulsation theories to these objects, as both allow to independently determine the masses of these stars. A detailed calculation and comparison of Cepheid "evolutionary masses" and "pulsational masses" was done in the 1960s, and led to the annoying result that the masses derived from pulsation theory were about 20-30% smaller than those obtained from the evolutionary tracks on the Hertzsprung-Russell diagram appropriate to Cepheid stars. Unfortunately the accuracy of the Cepheid masses derived empirically from single-lined and non-eclipsing systems was not good enough (about 30 % typically) to verify which prediction was right. In the course of Araucaria we have studied for the first time ever several Cepheids in eclipsing binaries. Based on these unique systems we measured physical parameters (like mass, radius, etc) of Cepheids with an unprecedented precision close to 1%. Our results definitively showed that the predictions of pulsation theory were correct. In general they allowed to understand Cepheids much better, making them a more reliable tool for distance determination. These unique systems provide us also with an opportunity to obtain the distance to the same object using Cepheids, and – independently – eclipsing binaries, and therefore to test the precision and accuracy of both methods.



>> Fig. 4: Range and precision of the geometrical methods which can be used to calibrate absolute cosmic distances. As can be appreciated, the eclipsing binary method calibrated by the Araucaria Project offers 1% precision distances out to the outskirts of the Local Group of galaxies (i. e. 1000 times larger than any other geometrical method). With the advent of new extremely large telescopes, in the near future we will be able to reach much farther.
Image credit: M. Górski.

Our results and discoveries were published in about 200 refereed papers (five of them in *Nature*), reporting about 100 precision distance determinations. Our very simple and powerful method based on eclipsing binaries, frequently called the Polish cosmic ruler, provides a unique possibility to measure geometrical distances accurate to 1% up to distances of 1 Mpc. For example, the Gaia satellite is expected to deliver such precise distances only for stars located 1000 times closer (see Fig. 4). Therefore, our method is the only one which can be used to measure geometrical distances to nearby galaxies. We also published precision (0.2-2%) stellar parameters for some 100 stars (including seven Cepheids) in the Milky Way, LMC, and SMC. Therefore, our results have a strong impact not only on cosmology and Hubble constant determinations, but also on most studies of galaxies, stellar astrophysics, stellar evolution and pulsations.

In spite of such a big progress on the calibration of the extragalactic distance scale accomplished by the Araucaria Project and other teams, a lot of work is still required before we can use the full potential of the classical Cepheid – SN Ia approach to massively measure geometrical distances to nearby galaxies, and to determine the Hubble constant. Thanks to several satellite missions like TESS and *Gaia* outstanding data for eclipsing binaries, Cepheids, and other distance indicators in the Milky Way will be obtained. To take the full advantage of this situation we will perform complementary observations of these objects with a wide variety of telescopes and instruments including the telescopes in our dedicated Cerro Armazones Observatory. These data will allow us not only to significantly improve the Polish cosmic ruler, but also to develop new techniques to measure geometrical distances to nearby galaxies.

Therefore, the Araucaria Project will keep being very important in front-line studies about the basic questions on the nature of the Universe. Our distance determinations and studies of objects in different environments will be central in one of the most challenging and passionate endeavors in astrophysics: to measure the Hubble constant with a 1% precision and accuracy. This should help us to understand the physical nature of the enigmatic dark energy as well as to verify and eventually explain the current crisis related to the discrepancy of the Hubble constant determinations with different techniques.

Our research will have an impact on many different fields of modern astrophysics (from studies of the local vicinity, through stellar astrophysics, studies of galaxies up to cosmology), and you are encouraged to join us. We will provide an excellent environment for your researchers to work in a very active international team to construct and expand their careers at different levels. In particular the younger generation of astronomers (master and PhD students) will find an opportunity for very interesting project in several fields of astrophysics, programming, and astronomical instrumentation.

>> Fig. 5: Araucaria team members during our biannual meeting held in 2019 in Concepcion, Chile. Headed by me, the team consists of about 30 astronomers from several countries. Its core group is associated with CAMK PAN, and comprises Marek Górski, Dariusz Graczyk, Gergely Hajdu, Mikołaj Kałuszyński, Paulina Karczmarek, Weronika Narloch, Bogumił Pilecki, Grzegorz Pietrzyński, Wojtek Pych, Gonzalo Rojas Garcia, Radosław Smolec, Ksenia Suchomska, Mónica Taormina, Piotr Wielgórski, and Bartłomiej Zgirski.
Image credit: C. Burgos.

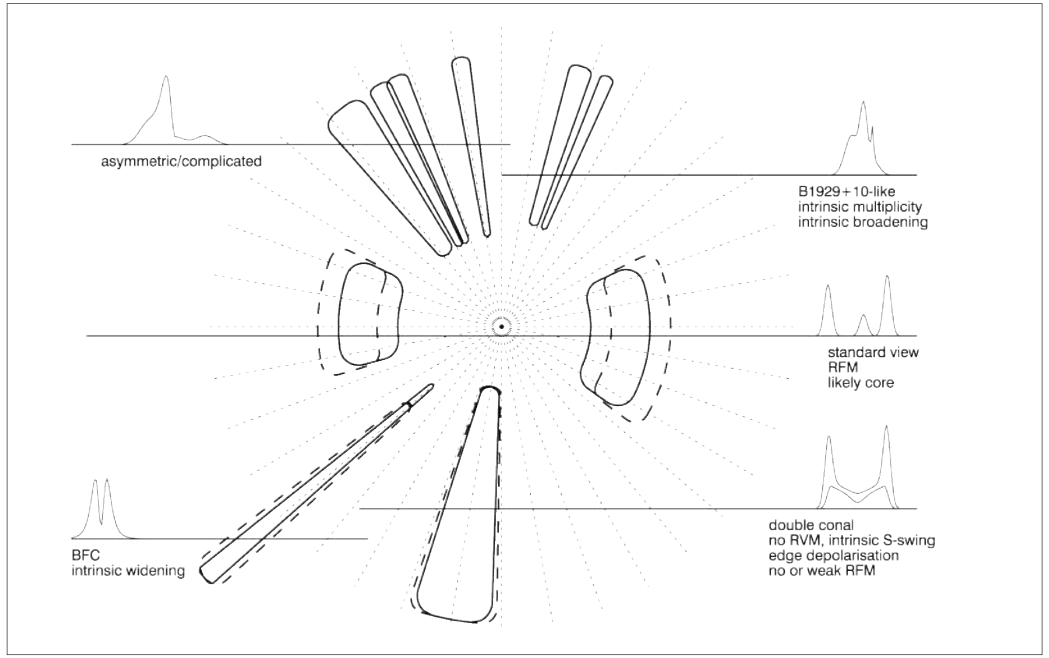
**Jarosław Dyks and Bronisław Rudak**

# Pulsar studies

Members of pulsar group at CAMK PAN study radiative properties of pulsars, ie. pulse profiles, polarization and spectra. Pulsars are compact stars that exhibit enormous range of mysterious phenomenology which is poorly understood despite half a century of research and observation.

One noteworthy result that we have obtained is the prediction of very unorthodox shape of radio pulsar beam: a system of fan beams instead of traditional concentric cones (Dyks, Rudak & Demorest 2010, the two types of beams are compared in the first two figures of this note). The new geometry has been invoked from observations of peculiar bifurcated features observed in pulsar profiles. In the following years the fan beam geometry has been confirmed by beam mapping through the long-time-scale observations of precessing pulsars in binary systems (Desvignes et al. 2019).

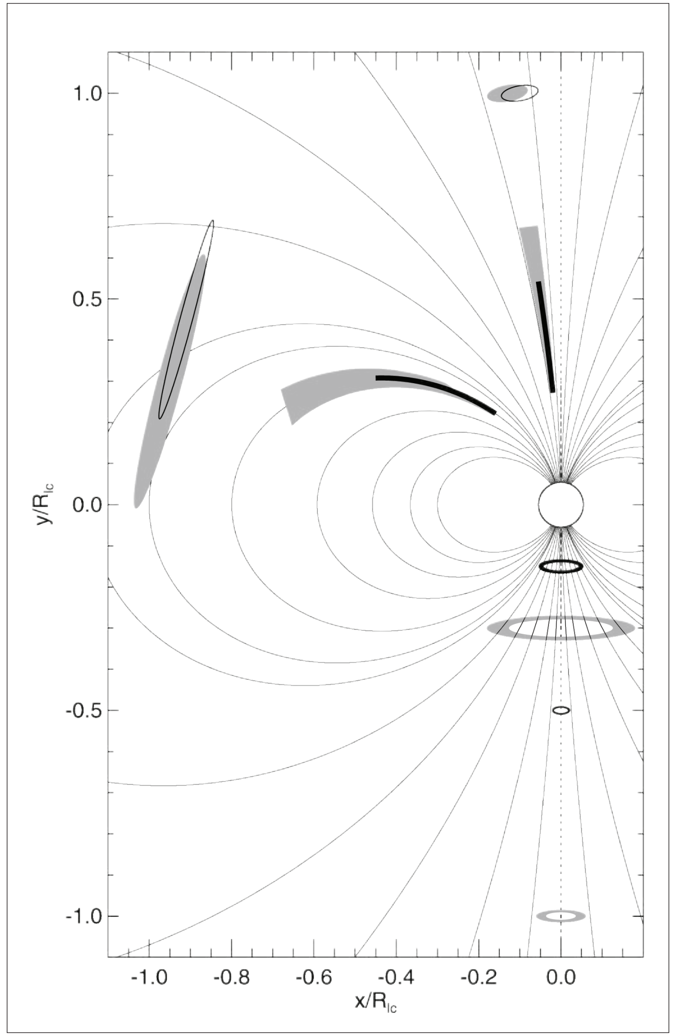
Because of the fast (subrelativistic) rotation, pulsar profiles and polarization are strongly affected by effects of aberration, retardation and corotational acceleration. This allows us to localize emission regions in pulsar magnetosphere (Dyks & Rudak 2003; Dyks 2008; Dyks, Wright & Demorest 2010). The third figure presents trajectories of electrons that are outflowing in corotating dipolar magnetosphere, as observed in the noncorotating observer frame.

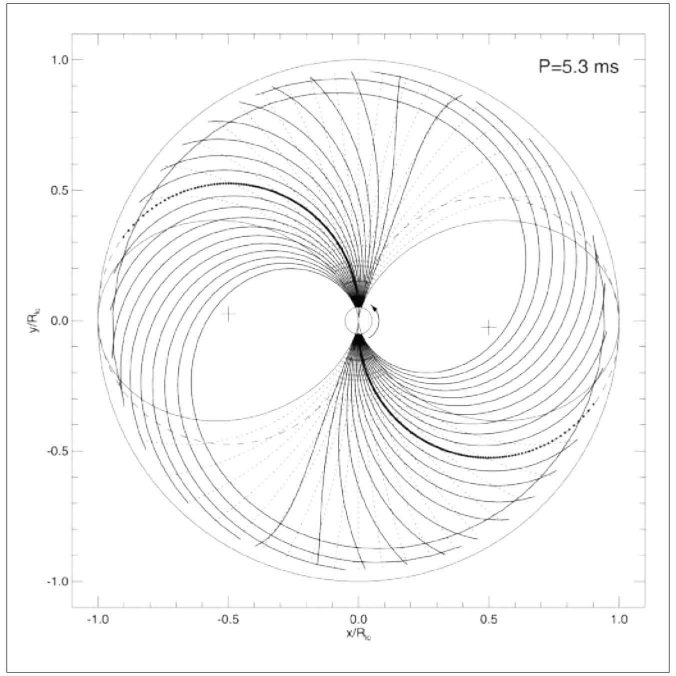


>> Fig. 1: Head-on view of pulsar radio emission region (contours) in dipolar magnetic field (dotted lines, the central dot is the dipole axis). Horizontal lines present the paths of sightline which moves because of star rotation. The middle case shows the traditional conal model (part of axis-centred ring, dashed contours refer to a lower frequency). The other cases present the fan beam model (Dyks, Rudak & Demorest 2010). RFM = radius to frequency mapping, BFC = bifurcated components, RVM = rotating vector model (polarization angle swing of RVM type).

Radio pulsar polarization has long been considered crucial for determining general geometry of pulsar magnetic field (dipolarity, tilt of magnetic moment off the rotation axis), however, the observed polarization angle is strongly distorted by superposition of radiation in two orthogonal polarization modes. Our recent pulsar studies focus on deciphering the distortions to uncover the underlying geometry and physics.

*Desvignes, G., Kramer, M., Lee, K., et al., 2019, Science, 365, 1013*
*Dyks, J. & Rudak, B., 2003, ApJ, 598, 1201*
*Dyks, J., 2008, MNRAS, 391, 859*
*Dyks, J., Rudak, B. & Demorest, P., 2010, MNRAS, 401, 1781*
*Dyks, J., Wright, G.A.E., & Demorest, P., 2010, MNRAS, 405, 509*





>> Fig. 3: Observer-frame trajectories (thick solid lines) of electrons that move along the dipolar magnetic field which corotates with the neutron star. Thin lines are the B-field lines at the moment when the charges leave the star surface. Dots that merge into thick solid line present the motion along the straight dipole axis. Vacuum static-shape dipole was assumed with no distortions near the light cylinder.

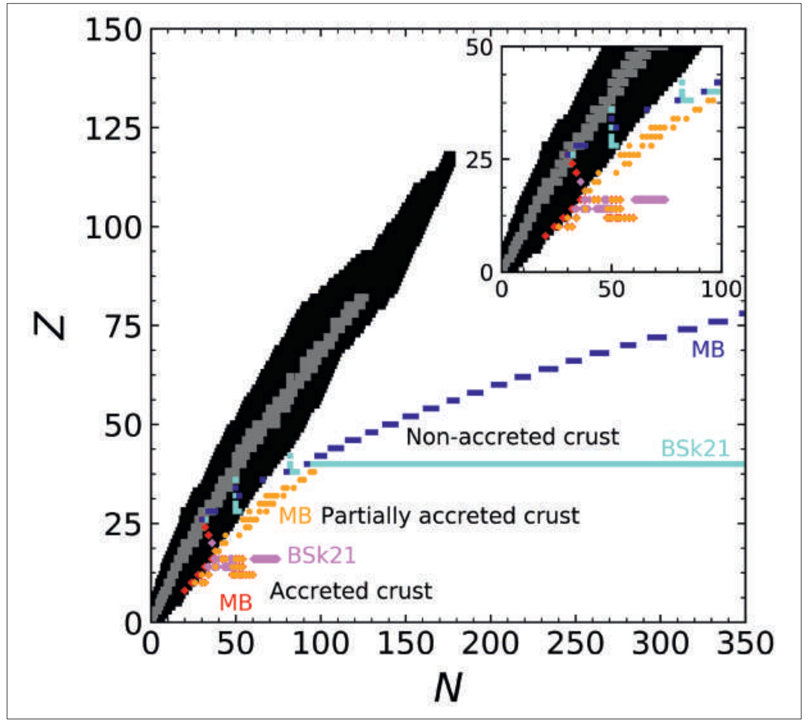
>> Fig. 2: Side view of radio emission regions in the fan beam model (top) and the conal model (bottom). Grey colour corresponds to a lower frequency. The ellipses near the top and left margin present the sky-projected emission in the fan beam model. Rlc = radius of light cylinder.

**Julian Leszek Zdunik, Morgane Fortin**

# Neutron stars: astrophysical laboratories for nuclear physics

Neutron stars are born in the supernova explosion that marks the end of the life of stars with a mass around 10 to 30 times the one of the Sun. So far about 3000 neutron stars have been observed with radio, infrared, optical, UV, X-ray, and gamma-ray telescopes and gravitational wave detectors.

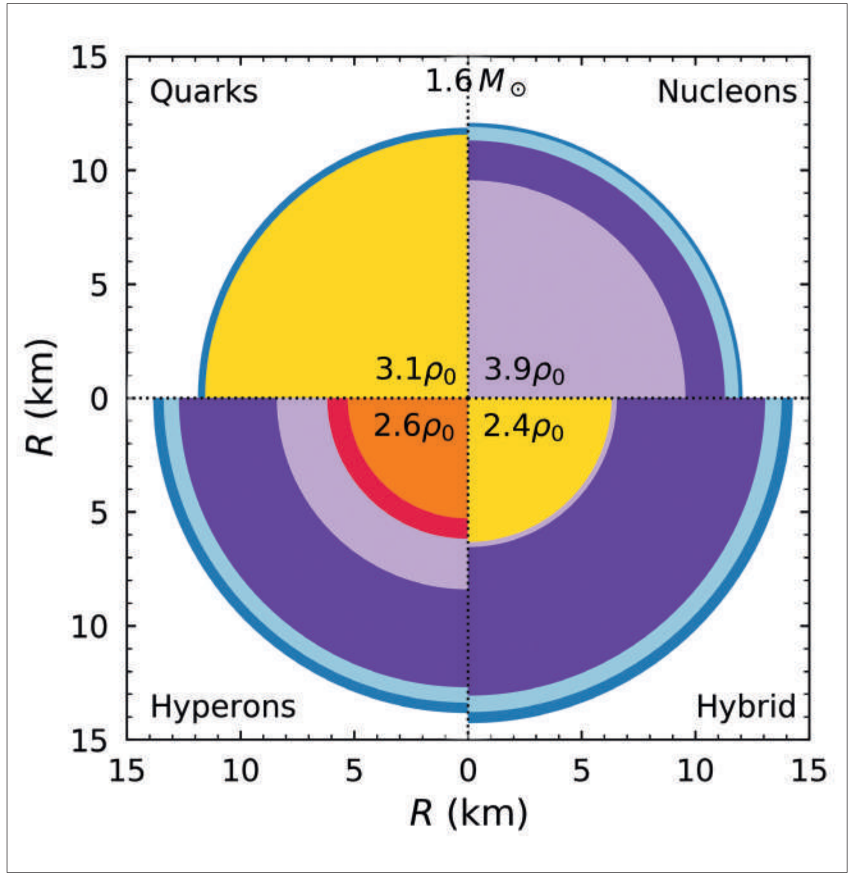
With a radius of about 12 kilometers and a mass of the order of 1 to 2 solar masses, neutron stars are one of the densest forms of matter in our Universe: the average density inside them is a couple of times larger than the average density inside heavy atomic nuclei. Their structure and dynamics are ruled by General Relativity. In neutron stars gravity is counterbalanced by the nuclear forces acting between the particles present in their interior. The properties of the nuclear interaction at densities significantly higher than that of nuclei are mostly unconstrained and thus many models for it have been proposed in the last fifty years. This is the main field of research of the dense matter group at CAMK PAN for more than three decades.



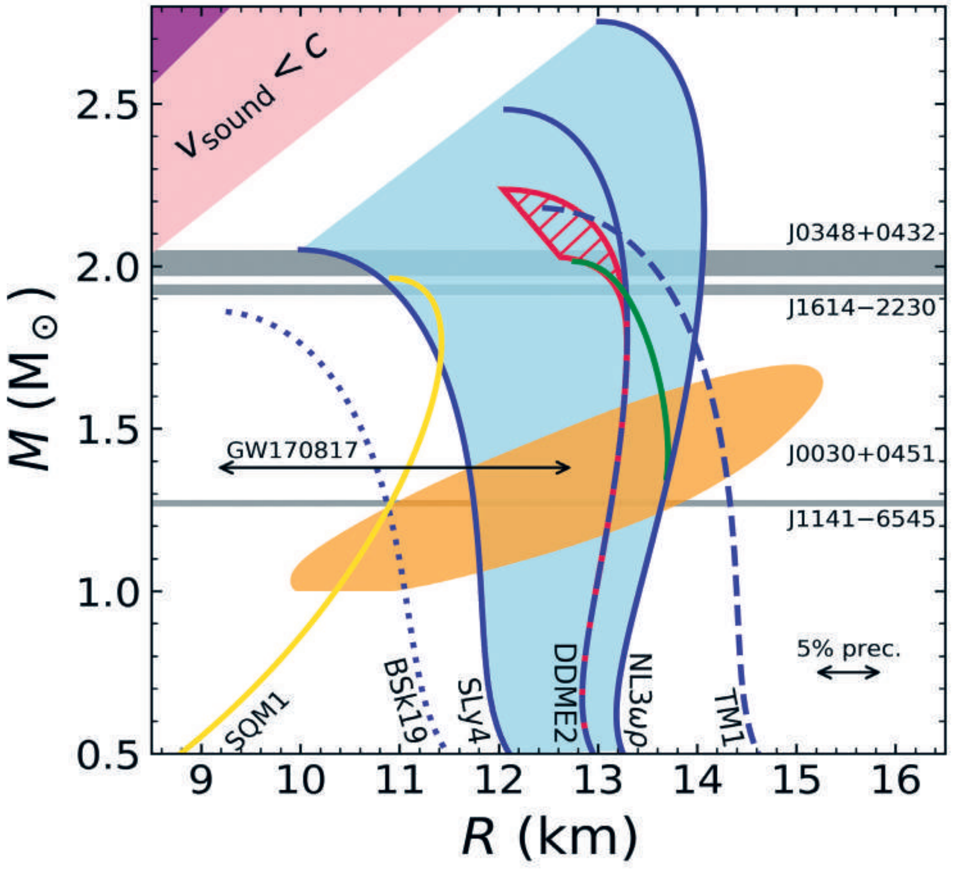
>> Fig. 1: Number of neutrons (N) and number of protons (Z) of: in black all nuclei produced in laboratory, and in color nuclei predicted in the crust, the upper part of neutron stars, for two different description of the nuclear interaction (known as MB and BSk21).

As their name indicates, neutron stars are mostly composed of neutrons, which are in the interior ten times more numerous than protons, contrary to our matter on Earth, where numbers of protons and neutrons are roughly equal. The outer part of neutron stars, called the crust, consists of nuclei immersed in electron and neutron gases. Nuclei that two nuclear models predict in the crust of neutron stars are plotted in Fig. 1. Most of these nuclei contain many more neutrons than ones produced in accelerators. Hence matter composing the major part of a neutron star can not be produced and examined on Earth and its properties can be reliably predicted only for densities up to the average density inside atomic nuclei. In other words neutron stars are a unique “cosmic laboratory” to study nuclear physics in ranges of densities and temperatures not reachable in terrestrial accelerators. The properties of the matter inside neutron stars and the composition of their interior in particular in the neutron star core, the innermost part, are still poorly known. Figure 2 shows the structure of a neutron star for four examples of models of the core.

To a given nuclear model, and thus composition of matter, corresponds a specific relation between the mass and radius of neutron stars. Some examples are presented in Fig. 3. So far the mass of about 60 neutron stars have been precisely measured thanks to observations with radio-telescopes. In the last few years constraints on the radius of a few neutron stars have been obtained with X-ray observations and gravitational wave detections.



>> Fig. 2: Structure of the interior of a neutron star with a mass of 1.6 times the one of our Sun for various models of the nuclear interaction. A neutron star is composed of two parts: the crust, in blue in all models, and the core. Some models predict that only nucleons - neutrons and protons - are present in the core (top right), others that the core is only made of deconfined up, down and strange quarks (top left), or that hyperons - particles with a strange quark - appear deep inside the core (bottom left) or lastly that the core is an hybrid, where quarks replace nucleons in the very center. The central density for each model is indicated in terms of $\rho_0$, the average density inside heavy nuclei.

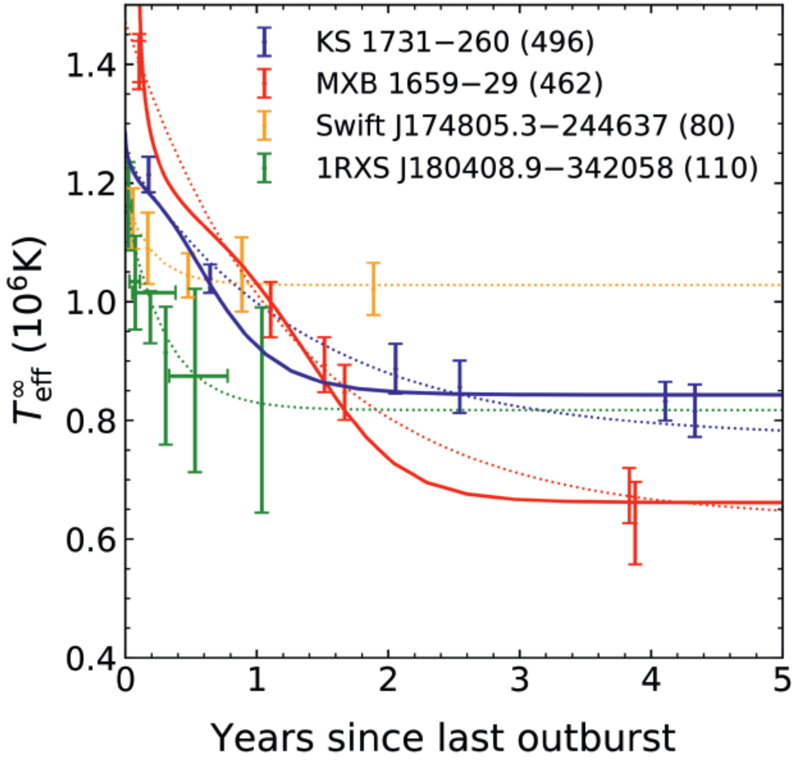


>> Fig. 3: Relation between the neutron star mass in units of the mass of the Sun and radius in kilometers for various models of the nuclear forces and composition of the core: quark core in yellow, only nucleons in violet, with hyperons appearing inside the core of massive stars in red and with a hybrid composition of a quark phase surrounded by a nucleonic one in green. The horizontal grey strips represent the precisely-determined masses of the lightest and heaviest neutron stars observed so far. The orange ellipsoid shows the constraints obtained on the mass and radius of the neutron star J0030+0451 by the NICER satellite currently operating onboard on the International Space Station. The ATHENA satellite which will be launched in the years 2030s is expected to provide accurate measurements of the radius (with a 5% precision). Each nuclear model predicts a maximum mass which is required to be larger than the mass of the heaviest observed neutron stars in order to be consistent with observations. As the maximum mass for the BSk19 nuclear model (dotted line) is smaller than the one of the very heavy neutron star J1614-2230, this model can be ruled out. The TM1 model (dashed line) can also be excluded as it is not consistent with the properties of matter for densities smaller than the ones in nuclei, measured using accelerators on Earth. The blue area covers ranges of mass and radius obtained for nuclear models that are consistent with nuclear experiments on Earth and astrophysical observations at the same time. The red striped-area shows the uncertainty on the mass and radius of stars with hyperons in the core due to the fact that the properties of these particles are barely constrained by laboratory measurements. The detection by the LIGO-Virgo collaboration of gravitational waves emitted during the merger of two neutron stars GW170817 puts additional limits on the radius allowing to rule out some nuclear models and thus further constrain the properties of the nuclear interaction.

Combined with laboratory measurements, these already allowed to rule out some models for the nuclear interaction. More precise and numerous radius measurements and constraints are expected in the next decade with sensitive X-ray telescopes like NICER and ATHENA and the gravitational wave detectors of the LIGO-Virgo-Kagra collaboration.

Current X-ray satellites allow us to measure the surface temperature of a number of neutron stars and in particular of some that are in a binary system with another star. Neutron stars in such systems are observed to, from time to time, attract matter from their companion star onto their surface: this is the so-called accretion process. The surface temperature just after accretion stops has been observed for over a couple of years for about ten neutron stars. Observations are plotted for four of them in Fig. 4 together with theoretical models obtained by us. These are able to reproduce the slow relaxation exhibited by two of them but not the faster one of the two other neutron stars. Current research at CAMK PAN attempts to find a physical model to explain the fast relaxation which is observed from most neutron stars after they stop accreting matter.

Neutron stars are cosmic laboratories at the interface between astrophysics and nuclear physics. The dense matter group at CAMK PAN computes models for the nuclear interaction and the neutron star interior and models various properties of neutron stars. Confronting them with constraints obtained from multi-messenger observations and results of nuclear experiments in laboratories will help to better understand the properties of the nuclear forces.



>> Fig. 4: Evolution of the surface temperature of four neutron stars since they stopped accreting matter from their companion star. The number in parentheses in the caption is the time-scale in days of the thermal relaxation, obtained with simple fits of the observations (dotted lines). The solid lines are the results of theoretical calculations: currently only the observations of the first two objects which are slowly relaxing can be reproduced. A physical explanation for the fast relaxation on a time-scale of a hundred days and observed for most neutron stars has not been found yet and is the subject of active research.

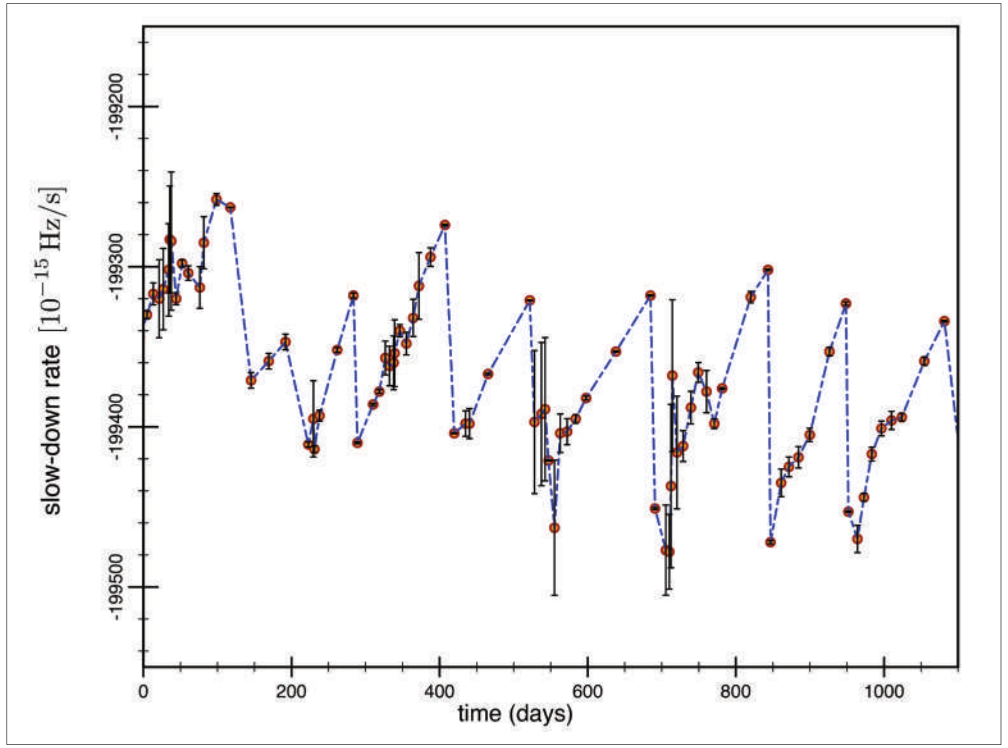
**Brynmor Haskell**

# Superfluids in neutron stars

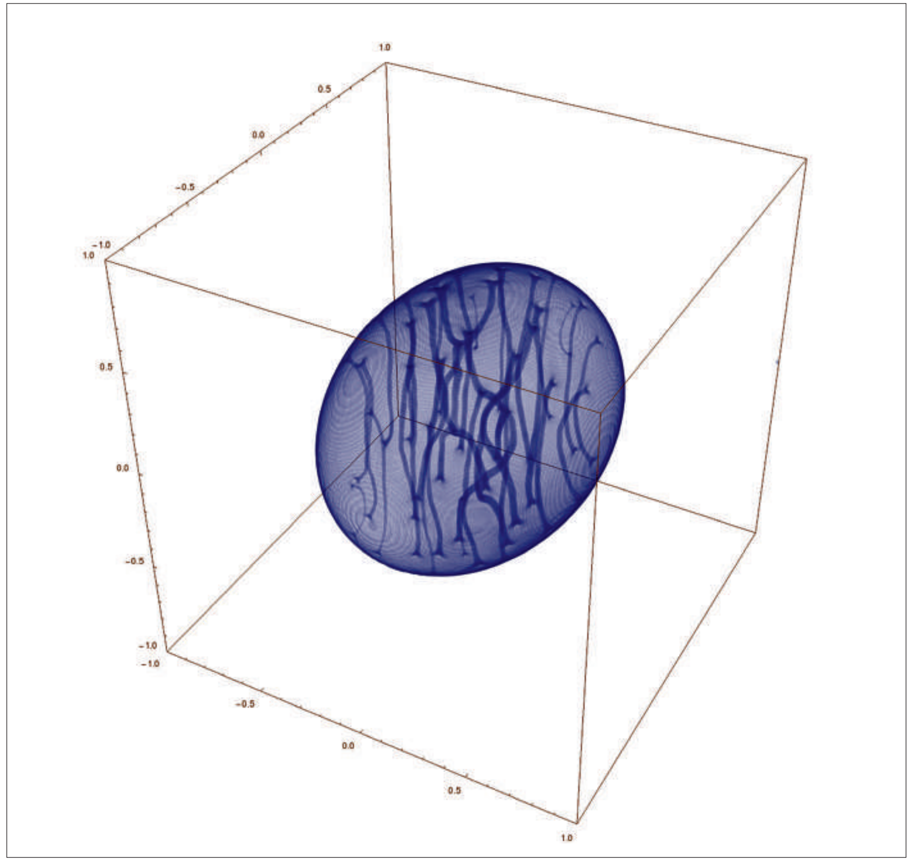
Neutron stars are not only remarkable astronomical objects, but they are also one of the most extraordinary fundamental physics laboratories we can imagine. There interiors are not only incredibly dense, but also 'cold'.

This may seem surprising, as the interior temperature of a mature neutron star can be of over a million degrees. However, at the extreme densities that characterise the interior of these stars, the thermal energy at such temperatures is still negligibly small compared to the interaction energy of the microphysical components. This means that a neutron star interior will behave in a similar way to atomic gases in terrestrial laboratories, when cooled to temperatures close to absolute zero, i.e. it will be superfluid.

Superfluidity allows for a rich phenomenology: it is well known from laboratory experiments with helium that a superfluid can flow relative to its container with little or no friction. Strikingly such a phenomenon observed on small scale on Earth is thought to be at the base of large scale astronomical events: pulsar glitches. Glitches are sudden jumps in the rotational frequency of pulsars (magnetised neutron stars) first observed by radio astronomers at the end of the 1960s. They are thought to be due to the sudden exchange of angular momentum between superfluid and normal components of the star, but 50 years after their discovery many details of the coupling between these components are still being investigated.



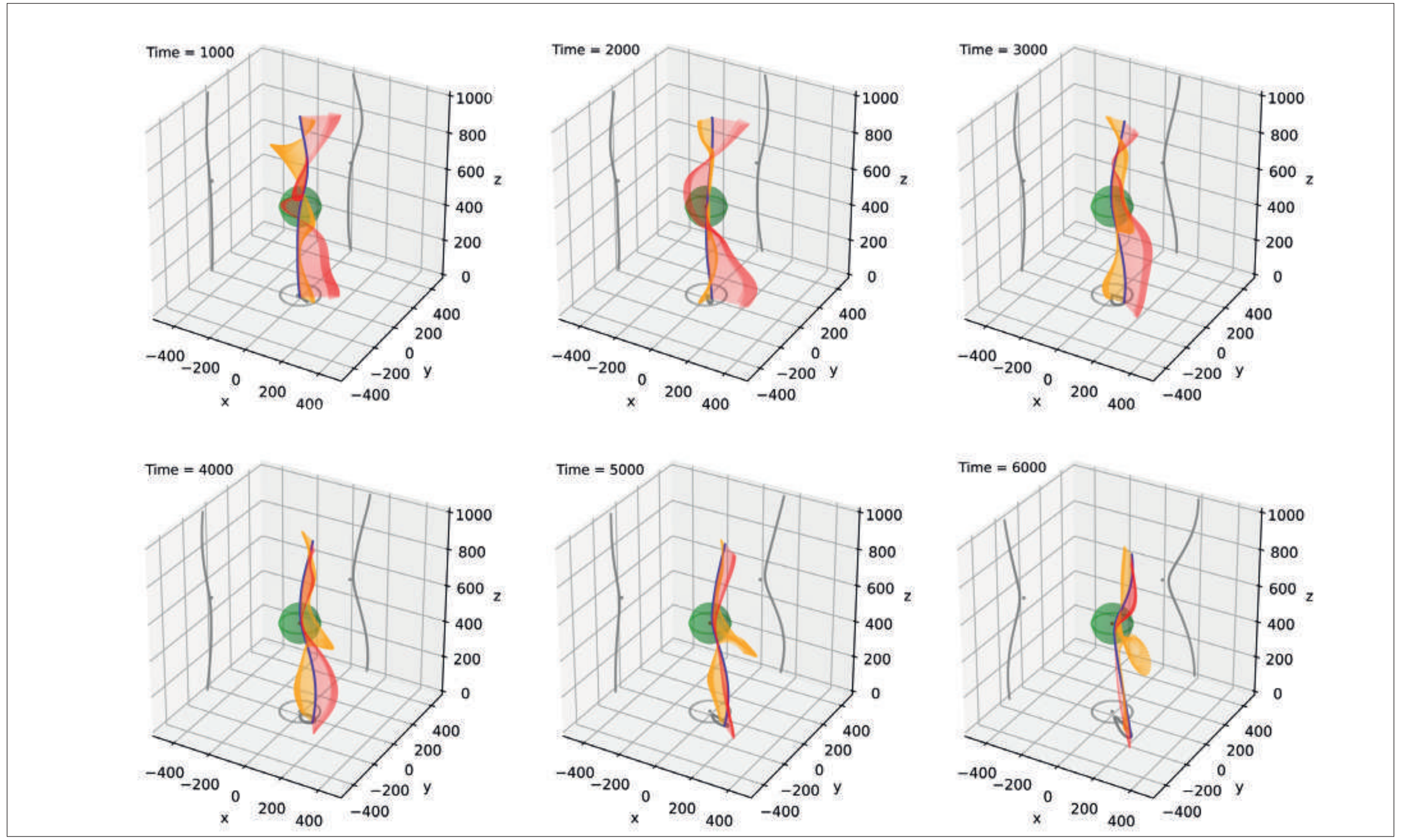
>> Fig. 1: Example of changes in the slow down rate following glitches in the Vela pulsar



>> Fig. 2: Numerical simulation of a droplet of superfluid - a `neutron star' in the laboratory

Theoretical models of superfluid neutron stars are needed to interpret not only data from pulsar glitches, but also produce models of gravitational wave emission. To develop such models it is necessary to master techniques developed for laboratory superfluids, and devise methods to extend them to considerably larger systems, the size of a star! Our group at the CAMK PAN works on this problem from several angles, but running state of the art computer simulations on one side, and comparing the results to astronomical observations to constrain microphysical parameters on the other.

One of the main differences between a superfluid and a classical fluid is that a superfluid condensate is described by a macroscopic quantum wave function, and is irrotational. This means that it mimics solid body rotation by creating an array of quantum vortices. It is



>> Fig. 3: Motion of a vortex filament past a nucleus in the crust of a neutron star

precisely the motion and interaction of the vortices with the normal components of the star that is thought to give rise to glitches. To understand this mechanism we set up a laboratory equivalent of the neutron star: a spherical 'drop' of rotating superfluid that can be studied by integrating numerically the Gross Pitaevskii equations, and also extract its behaviour to larger scale systems with the use of vortex filament simulations in 2 and 3 dimensions. The parameters that we extract from these microphysical simulations are then used in hydrodynamical glitch models, including also the effects of Einstein's theory of General Relativity. Our models are then compared to observations and used to interpret data from glitches in pulsars such as the Vela and Crab pulsars, or the most prolific glitching neutron star: the young X-ray pulsar J0537-6910.

Our group at the CAMK PAN is also active in searching for gravitational wave signature associated with pulsar glitches, and in general with modes of oscillation of superfluid neutron stars. We are part of the Polish POLGRAW consortium which works on detecting these kinds of signals in the data from the LIGO, Virgo and Kagra detectors.

Team members: Marco Antonelli, Danai Antonopoulou, Brynmor Haskell (head), Vadym Khomenko.

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**Krzysztof Belczyński**

# Astrophysics of gravitational waves

The construction of the gigantic U.S. Laser Interferometer Gravitational Wave Observatory (LIGO) and the European Virgo Observatory has led to the direct discovery of gravitational waves in 2015. At the moment both observatories detect about one collision of compact objects every week. A new discipline of science has just been born: gravitational wave astronomy.

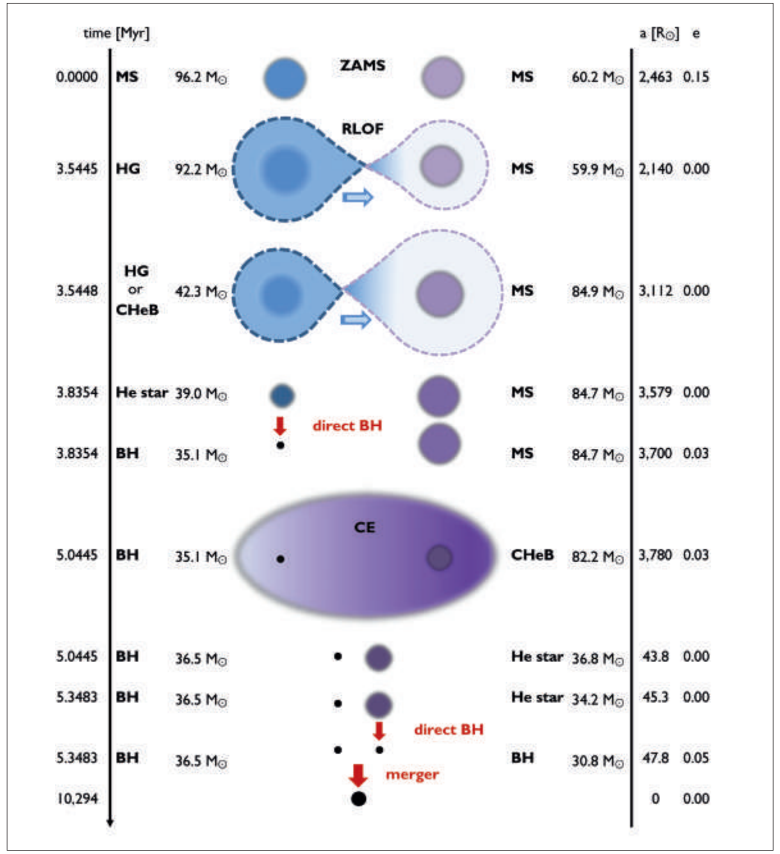
One of the most important predictions of Einstein's Theory of General Relativity were gravitational waves. Since this prediction, in 1915, scientists have been trying to prove (or disprove) the existence of gravitational waves. The first indication that they exist came in 1974. Russell Hulse and Joseph Tylor discovered a double pulsar system: a binary consisting of two neutron stars. The two orbiting neutron stars, according to Einstein's theory, should emit gravitational waves and therefore should be getting closer and closer to each other. In fact, such an approaching motion was measured, confirming the existence of gravitational waves (alas indirectly), and both scientist were awarded Nobel prize in 1994.

Following this indirect confirmation, astronomers have begun a long quest to detect gravitational waves directly. Gravitational waves distort spacetime; for example changing the distance between two free-floating masses. The stronger the wave the larger the displacement. However, spacetime is a very stiff medium, and the expected displacements are extremely small. So only the most violent and catastrophic events may possibly generate waves strong enough to be measurable. Astronomers have identified such catastrophic events looking through the depths of the Universe. In general, two orbiting neutron stars or black holes do not emit waves strong enough to be directly detectable on Earth. However, if such two compact objects are accelerated to speeds that are a significant fraction of the speed of light, and if they collide (for example in a binary star system) then such a crash is potentially detectable.

CAMK PAN runs a program Universe@home to study potential sources of gravitational waves and extract astrophysical information from current and future LIGO and Virgo detections. This new discipline of science, gravitational wave astronomy, offers a qualitatively new insights into the workings of Universe. My group studies the evolution of stellar populations that were born across cosmic time. Massive stars are the progenitors of neutron stars and black holes that are prime sources of gravitational waves. Population studies carried out at CAMK PAN are on the frontier of information inference from LIGO/Virgo data. Evolutionary studies deliver insights into core-collapse supernovae, pair-instability supernovae, stellar wind mass loss, angular momentum transport in stellar interiors or evolution of chemical composition of Universe on large scales. Formation of compact objects, involves a number of long-standing problems in stellar astrophysics. Do all massive stars die in supernovae explosions? How do stars survive violent interactions in binary systems? What is the maximum mass of stellar-origin black holes? What is the role of neutron star mergers in enriching the Universe with the most heavy elements? What are the most likely evolutionary channels that produce sources of gravitational waves? In which galaxies do they preferentially occur?

So far our theoretical modeling was used to predict already in 2010 that massive black holes would dominate LIGO/Virgo detections. Our model was verified by the very first detection in 2015 and our results were used by the LIGO/Virgo collaboration to explain the formation of the detected massive black hole merger through classical binary evolution (see Fig.1). Currently we are taking full advantage of the existing LIGO/Virgo observations, developing a detailed physical model of the evolution of stars that form neutron stars and black holes. Our studies connect with those of Michał Bejger's group who is part of the Virgo collaboration. Our research is also complemented by another CAMK PAN group led by Mirek Giersz who studies evolution of dense stellar clusters that can also produce LIGO/Virgo sources.

Our computer model allows to create a synthetic Universe filled with stars and follow their evolution from the Big Bang to the present. Across the eons of time neutron stars and black holes are born and are tracked until they are detected by our artificial LIGO/Virgo observatory. The results depend sensitively on our assumed physics that sets birth, evolution and death of stars. Modifications of the physics (modeling) is guided by LIGO/Virgo observations (comparisons of our computer predictions with the real world) to get insights into inner workings of massive stars. Our heavy computations (billions of stars) are performed both on supercomputers and with the use of personal computers of a world-wide network of volunteers (through citizen science based program with over 30,000 users: 7th largest such science project in the world).



>> Fig. 1: Example of a binary evolution leading to the formation of a black hole -- black hole (BH-BH) merger similar to GW150914 (the first LIGO detection). A massive binary star (96 + 60 Msun) is formed in the distant past (2 billion years after Big Bang; z=3.2) and after five million years of evolution forms a massive BH-BH system (37 + 31 Msun). For the ensuing 10.3 billion years this BH-BH system is subject to angular momentum loss, with the orbital separation steadily decreasing, until the black holes coalesce at redshift z=0.09. This example binary formed in a low metallicity environment (Z=3% Zsun).

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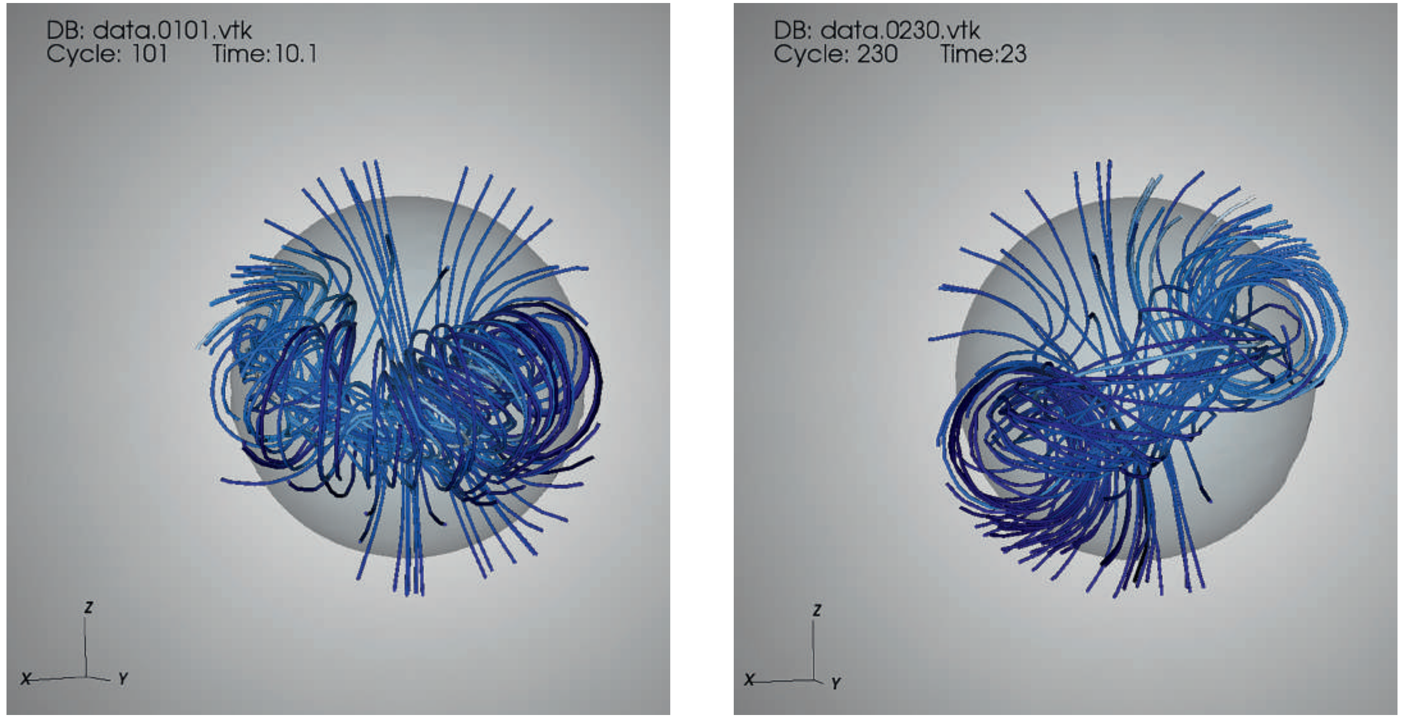
### Brynmor Haskell

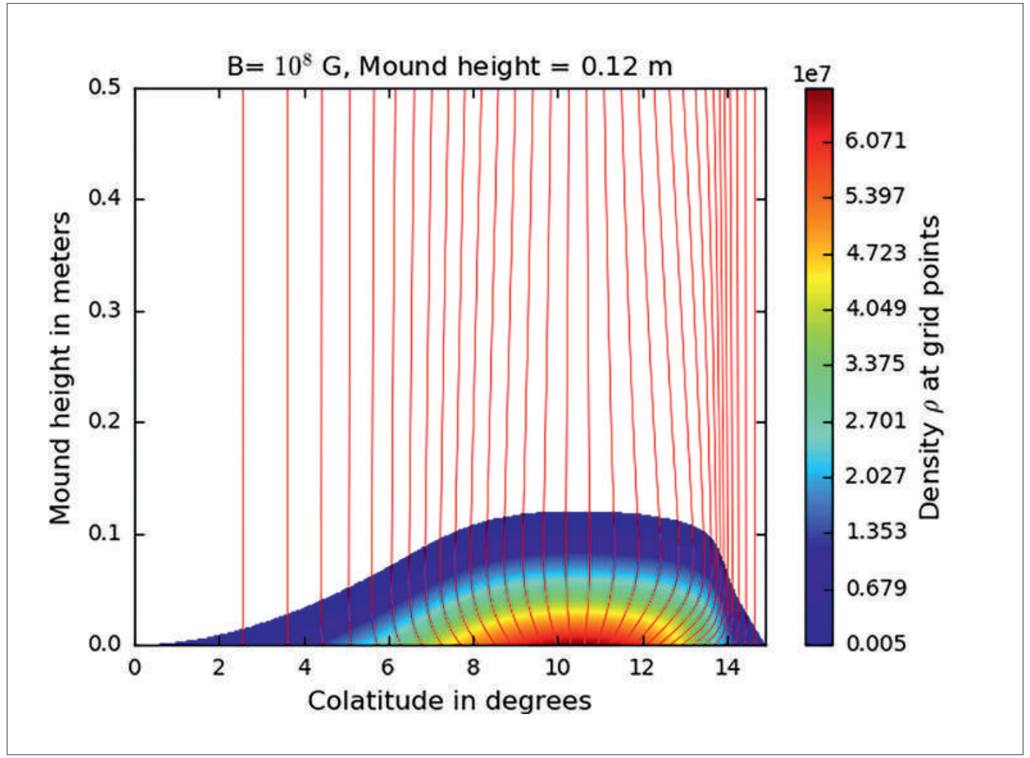
# Gravitational waves from neutron stars

Neutron stars are some of the most compact objects in the universe. With the mass approximately that of the sun compressed into a ten kilometre radius, only the quantum degeneracy pressure of neutrons prevents these incredible objects from collapsing into a Black Hole.

Spacetime is significantly deformed by neutron stars, and internal motions, such as modes of oscillation (similar to those observed in the sun and other main sequence stars), or irregularities in the rotation rate (due to superfluids in the interior, or to 'mountains' on the star) couple to the gravitational field and can generate gravitational waves. These waves are continuous in nature, the gravitational wave equivalent of the radio signal received from pulsars. Although weak they promise to deliver an unprecedented insight in the interior of neutron stars.



>> Fig. 1: MHD simulations of the magnetic field configuration of a neutron star



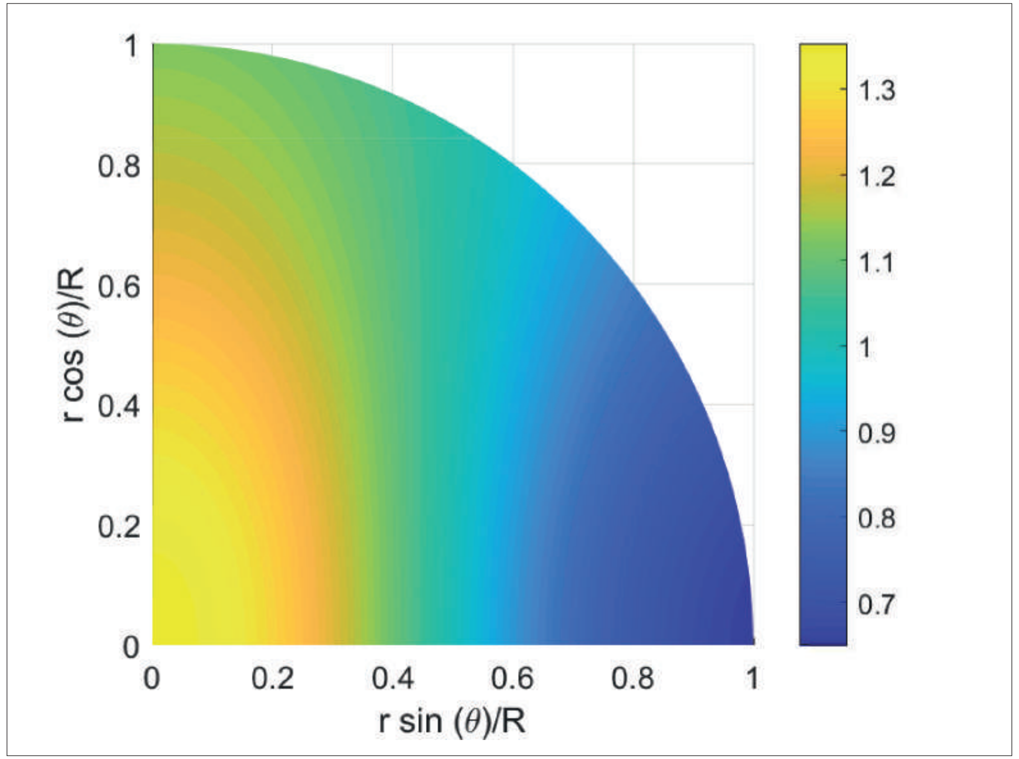
>> Fig. 2: Numerical MHD simulation of a mountain on an accreting neutron star.

In fact gravitational wave signals from far more violent events, the mergers of two neutron stars, have already been detected and allowed us to study the physics of dense matter in extreme conditions.

For all sources, however, theoretical models are needed to extract the signal from the noise in gravitational wave detectors such as LIGO and Virgo, and interpret the data to push forward our understanding of fundamental physics. Our group at the CAMK PAN works on theoretical models of gravitational wave generation in neutron stars.

We develop magnetohydrodynamical (MHD) simulations of accreting magnetised neutron stars, to understand if the accreted material can form a `mountain' on the outer layers of the star. This mountain will be low by terrestrial standards (a centimetre at the most before the crust cracks) but given the strong gravitational field, the change in potential energy is huge over such a distance, and the rotation of such an asymmetric mound will send out `ripples' in space time that detectors actively search for. Furthermore if exotic states of matter exist in the star, such as a core of deconfined quarks, this may harbour even larger internal deformations that can be detected by our instruments. In fact, it has been suggested that the observed spin frequency of a class of neutron stars that are accreting matter from their binary companions, the Low Mass X-ray Binaries (which are, as the name says, observed in X-rays), is dictated by gravitational wave torques, possibly due to such mountains.

Continuous signals can also be due to modes of oscillation in the star, `waves' in the interior that can reveal the structure of the star, much in the same way as solar oscillations allow us to study the structure of the sun.



>> Fig. 3: Relativistic corrections to the superfluid vortex density in a neutron star.

Our group at the CAMK PAN is active in both theoretical modelling of such oscillations, and in identifying promising targets for gravitational wave searches from electromagnetic observations of neutron stars (in X-ray, ultaviolet, radio and gamma ray).

We are part of the LIGO-Virgo-Kagra collaboration and provide theoretical guidance for searches of continuous signals in real gravitational wave data.

Theoretical models of gravitational wave signals from neutron stars require a deep understanding of not only the microphysical mechanisms at work in the interior, but also how to model such processes in Einstein's theory of General Relativity.

Our group is active in developing relativistic theories of dissipation. This is a complex problem, as for example one cannot use traditional methods of Newtonian hydrodynamics, such as the Navier Stokes equations, as these will produce signals that propagate faster than the speed of light and violate causality in General Relativity. Our efforts focus on constructing consistent theories for dissipation that can be used to model viscosity in neutron star mergers, but also study the effect of superfluidity in detail, including relativistic corrections. Although this has a subtle effect on the dynamics of the system, it can be, for example, discerned in observations of pulsar glitches by the new generation of radio telescopes, such as the Square Kilometre Array (SKA), which is coming online, and has the potential to probe the microphysical processes in the star.

Team members: Lorenzo Gavassino, Brynmor Haskell (head), Ankan Sur.

**Michał Bejger**

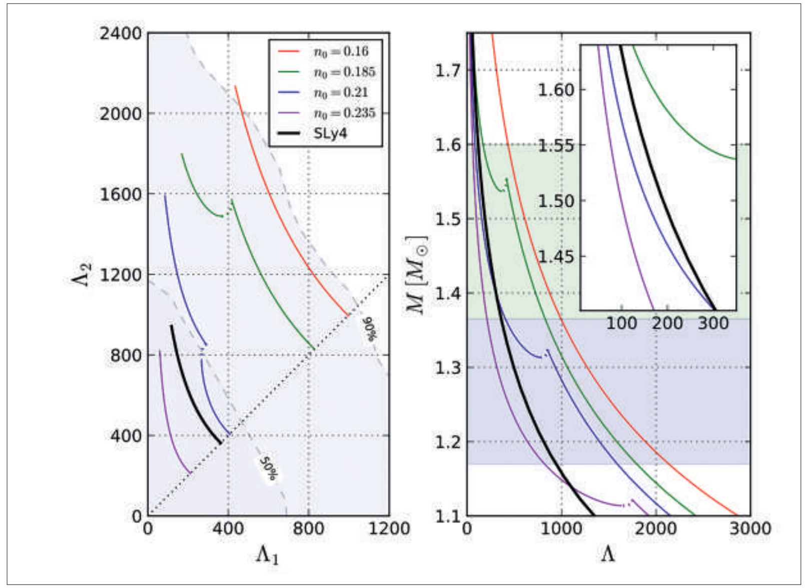
# Gravitational-wave astrophysics of compact objects: models, data analysis, machine learning

Modern astrophysics has reached the time in which the long-sought after direct gravitational-wave (GW) detections have become reality. GWs, ripples of spacetime that propagate at the speed of light, are produced by rapidly moving, massive and compact astrophysical objects with time-varying mass-quadrupole moments. GWs probe the most extreme astrophysical sites: the interior of neutron stars with their dense matter equation of state, the strong-gravity regime of neutron star and black hole mergers, hot collapsing supernovæ cores and gamma-ray burst engines.

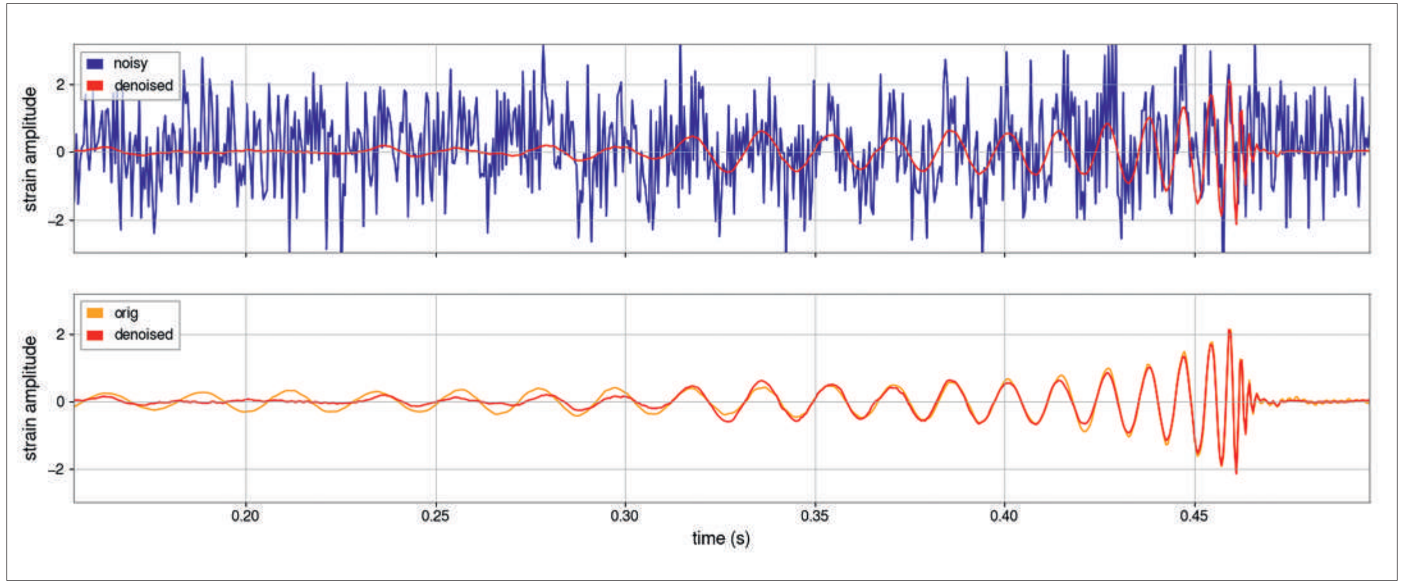
Contrary to photons, GWs do not couple strongly to matter, but they can be detected by measurements of the tidal effects they induce. They carry information inaccessible to electromagnetic observations and due to that are complementary to the main channel by which the Universe was studied so far. Reliable models and analysis of the GW data gathered in the Advanced LIGO and Advanced Virgo interferometers allows us therefore to study the Universe from a completely different perspective.

Our research group at CAMK PAN is closely collaborating within the LIGO-Virgo collaboration on both the data analysis and astrophysics of the signals. We are actively pursuing searches for GWs of all possible durations: short (cataclysmic), transient and long-lasting GW signals. Specifically, we are interested in those featuring neutron stars - the densest material objects known to science - in order to compare these observations with our best astrophysical models: to learn the details of their composition (elementary particles and interactions that constitute them) structure (global parameters such as mass, radius, tidal deformability, moment of inertia) and various properties (such as elastic phases, superfluidity). Astrophysically, the sources of GWs are binary systems of neutron stars, but also neutron-star—black-hole systems, core-collapse supernovae explosions, and rotating non-axisymmetric neutron stars in wide binary systems with ''normal'' stars, as well as solitary objects. Information obtained using the GW data is then combined with available electromagnetic (neutrino, cosmic rays, …) observations in the multi-messenger astronomy paradigm.

GWs from neutron stars in tight binaries are emitted at frequencies to which LIGO and Virgo detectors are sensitive during the last minutes of the system's inspiral. We have observed such signals: GW170817 and GW190425, and more detections are coming. The last stages of the inspiral contain information about the masses, spins and mutual tidal deformation of the components, and hence provide a direct probe of neutron-star interiors. At CAMK PAN we model the imprint of the equation of state, elastic properties and possible exotic phases in the dense matter on these observations (see Fig. 1). After the merger, the newly-formed, hot and rapidly-rotating remnant also radiates GWs: we aim to detect and characterize this post-merger emission to assess the state of hot and dense matter. These conditions are very much



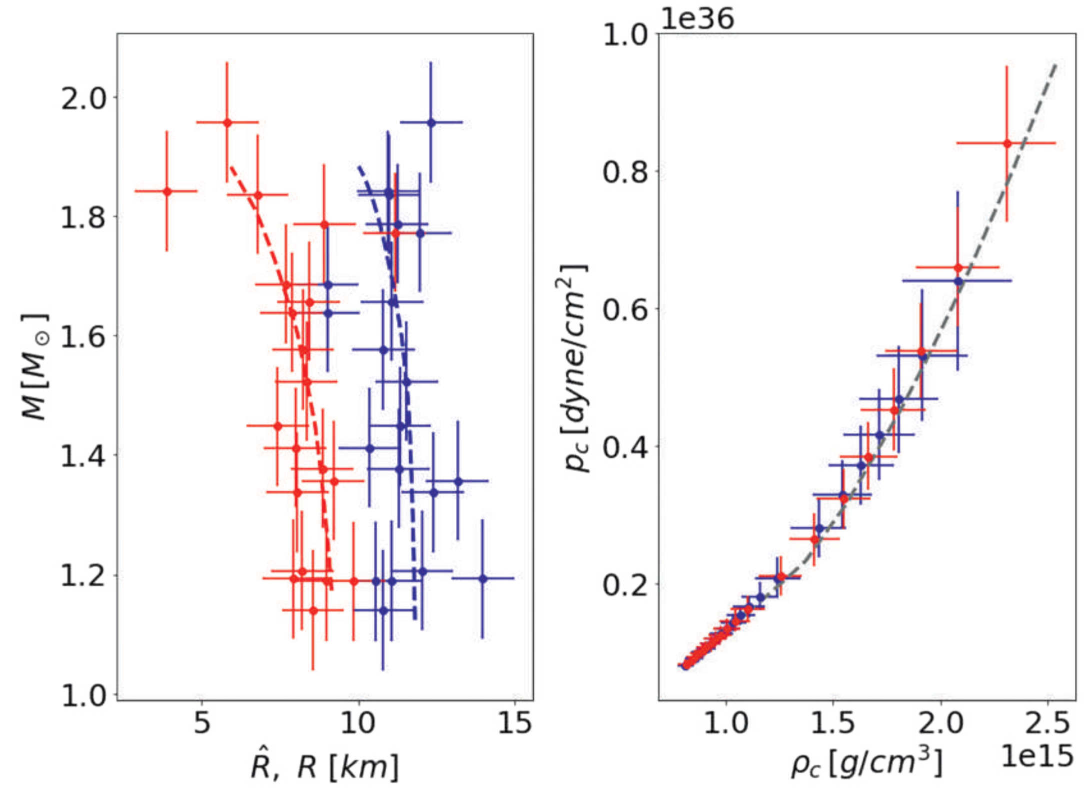
>> Fig. 1: Comparison of tidal deformability predictions for neutron star solutions with sizeable phase transition (colored lines), compared to the ''standard'' SLy4 equation of state (black line). The credible interval regions on the left plot and mass ranges on the right plot refer to the GW170817 event.



>> Fig. 2: Denoising of time-series gravitational-wave data. The data segment is whitened by the amplitude spectral density of the detector's noise and contains an astrophysical signal (black-hole binary system inspiral). Using a denoising auto-encoder based on 1D convolutional neural network architecture, one can effectively remove the noise using supervised training.

similar to those occurring in collapsing supernova cores, at the moment of a neutron star's birth. We are actively involved in searching for the core-collapse supernova ''GW bursts'' and in improvements of the sensitivity of these searches with machine learning methods.

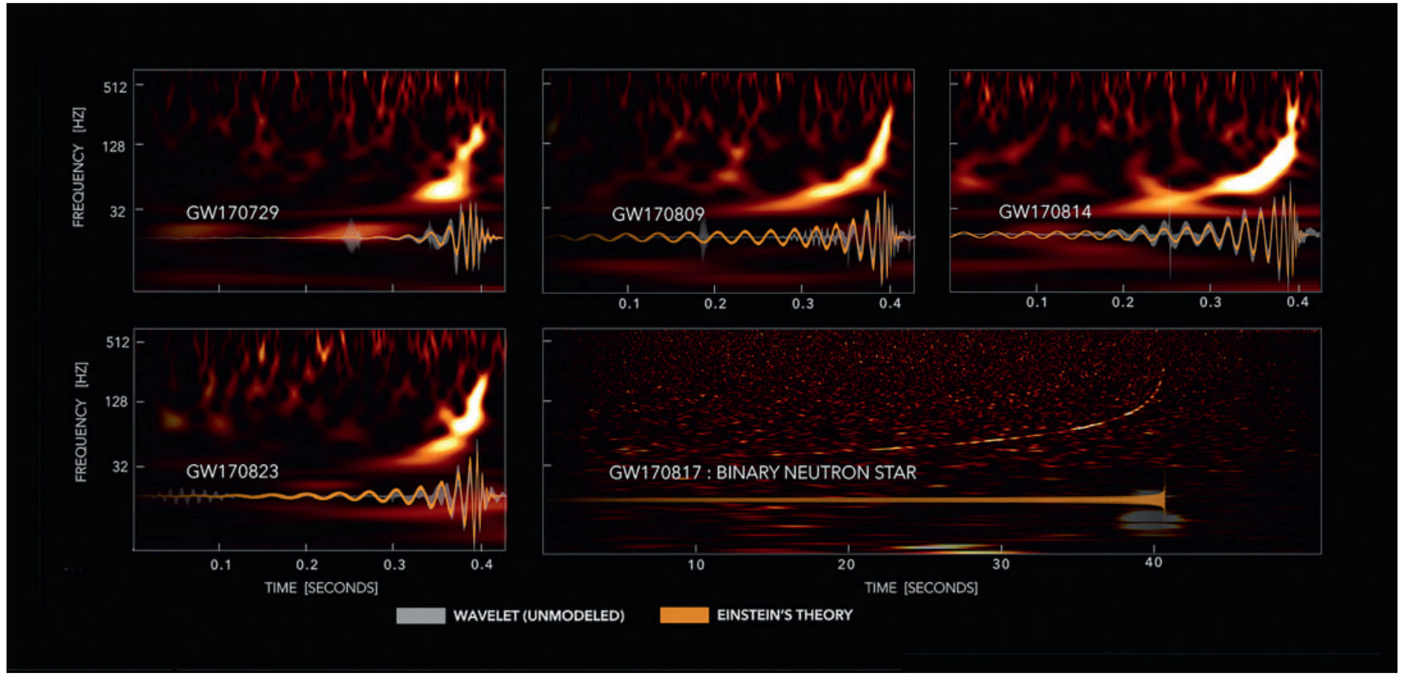
On the other side of the signal duration spectrum is the long-lasting (''continuous'') emission by rotating, non-axisymmetric neutron stars (''gravitational-wave pulsars''), which may be caused by the ''mountains'' created by thermal gradients and magnetic fields. We perform various targeted and all-sky searches for these long-duration signals on the LIGO-Virgo data with established data analysis methods (the F-statistics matched-filter approach), but also improve these methods to look for various types of transient neutron-star signals (related e.g. to the instabilities in the neutron-star interiors, like the r-modes, or post-glitch relaxation), creating a more flexible tool to study the transient GW sky.



>> Fig. 3: Artificial neural network applied to ‘‘invert’’ the hydrostatic equilibrium solutions of neutron stars in order to recover the microscopic input: the equation of state of extremely dense matter. Left panel - simulated observations of a theoretical mass-radius M(R) curve (blue dashed line and points with errors) and mass-tidal deformability radius M($\hat{R}$) curve ($\hat{R}$ is an analog of radius derived from the tidal deformability). Right panel - values of the equation of state (pressure-density relation), predicted from the ‘’observed’’ values of M(R) and M($\hat{R}$). The prediction is performed using an auto-encoder neural network, effectively solving the inverse of the Tolman-Oppenheimer-Volkoff equations.

In addition to traditional methods of the data analysis of very noisy data, such as the matched filtering, we research and implement modern alternative methods based on the usage of machine learning, specifically deep learning neural networks, to detect, classify, parametrize and denoise the data coming from the LIGO and Virgo detectors (e.g. Fig. 2). We use supervised training on pre-prepared sets of model results as well as unsupervised machine learning tools (clustering), to discover features hidden in the data and create algorithms capable of generalising specific ideas. e.g. infer the microscopic data from macroscopic observables of neutron stars (see an example in Fig. 3). Machine learning methodology is used to train intelligent algorithms capable of identifying and distinguishing detector artifacts from real GW signals, characterize them and even remove them from the data stream to improve the sensitivity. Solutions created at CAMK PAN have proved to be very useful both as main tools for the data analysis, and also to post-process the data obtained by other methods at all stages of their analysis.

Team members: Michał Bejger (head), Paweł Ciecieląg, Filip Morawski, Jonas Pereira, Magdalena Sieniawska.



>> Examples of real gravitational signals received from coalescing black holes (top frames, bottom left frame) and coalescing neutron stars (bottom right frame).
Image credit: LIGO, VIRGO, Georgia Tech / S. Ghonge & K. Jani.

**Włodzimierz Kluźniak**

# Accretion disks

Scientists of the CAMK PAN have made pioneering contributions to the understanding of accretion disks and accretion flows in general, and in particular they studied and modeled high-rate transfer of matter (accretion flows) onto compact bodies (black holes, neutron stars and white dwarfs).

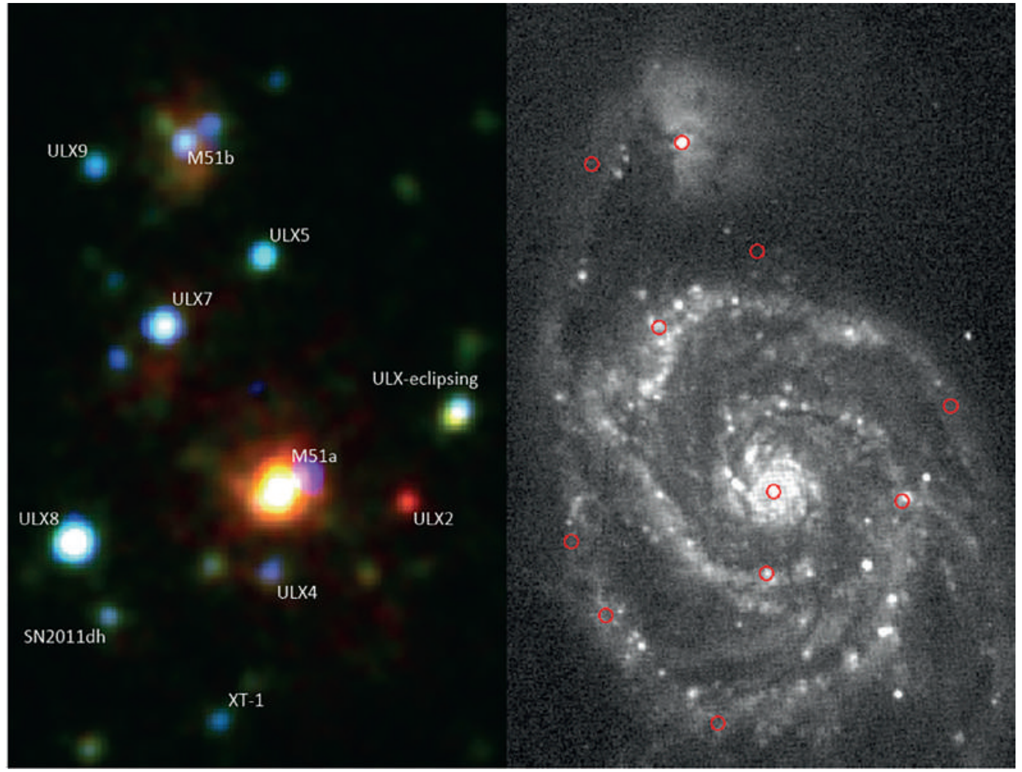
Accreting matter in black holes, neutron stars, and white dwarfs usually forms a disk-like structure, which is extremely luminous, and this explains the high X-ray brightness of X-ray binaries and of active galactic nuclei (AGN). The concept of accretion disks allowed a model of dwarf-nova outbursts, which is now widely accepted throughout the world to have been elaborated at CAMK PAN.

While theoretical investigations at our institute have now shifted to supercomputer simulations of the magnetohydrodynamics of accretion inflows and outflows in general relativity, analytic investigations of the structure of accretion disks was an early focus of research efforts here. Historically, much of this research was conducted in the framework of a pseudo-Newtonian potential introduced in the late 1970s by Bohdan Paczyński to accurately model the most important effects of Einstein's gravity in black hole accretion disks. Paczyński's pseudo-potential is still of great practical use in studies of the hydrodynamics and magnetohydrodynamics of accretion disks, and is routinely employed by many researchers everywhere. In particular it allowed the creation of an analytic model of very thick structures surrounding black holes with narrow funnels along the rotation axis capable to collimate radiation flux to moderately (or even very) super-Eddington values ("Polish Doughnuts").

Research on very luminous accretion flows has been recently renewed and continued in the context of the ultra-luminous X-ray sources (ULXs). These sources are defined by apparent (assumed isotropic) luminosities $L > 10^{39}$ erg $s^{-1}$, above the usual Eddington value for stellar-mass objects, but which do not contain supermassive black holes. When they were first identified around the turn of the century, the natural assumption was to regard these apparent luminosities as intrinsic, which then required that their accretors should be black holes with masses intermediate between stellar and supermassive. However, since the discovery, in 2014, that some of the ULXs contain, rapidly rotating, magnetized neutron stars, it is generally accepted that most (or possibly all) ULXs are otherwise normal stellar mass X-ray binaries in an unusual evolutionary state. One possibility is that their intrinsic luminosities do not significantly exceed the Eddington limit, but appear to do so when seen in a narrow range of viewing angles: they are not isotropic but collimated (or 'beamed') by the strong disk outflows generated by highly super-Eddington accretion.

Nicolaus Copernicus Astronomical Center researchers have developed a self-consistent model of pulsating ULXs (PULXs) that has defined the new paradigm describing these fascinating objects. According to this model, in PULXs an X-ray pulsar with an usual magnetic field ($10^{11}$-$10^{12}$ Gauss) accretes matter transferred from a massive stellar companion at rate that is highly super-Eddington. This matter forms an accretion flow around the neutron star from which a wind is blown out in regions where the flux is locally super-critical. This optically thick wind is the cause for the geometrical beaming of radiation that is allowed to escape only along narrow funnels. Although very successful in describing PULX properties, the model is, for the moment, rather simplistic and requires refinement mainly through numerical simulatios, which are an active subject of research at CAMK PAN. This research is also related to other problems of accretion astrophysics, in particular to the study of very large disks around white dwarfs, whose outbursts can lead to near-, or super-Eddington accretion and is combined with thermonuclear explosion of matter accumulated at the white dwarf's surface.

This research makes use of the observations provided by the present X-ray satellites XMM Newton, Chandra and NuStar, as well as the VLT and other large telescopes and is prepared to use the future instruments such as ATHENA and the EELT. The neutron star research notwithstanding, the more traditional investigations into accretion onto black holes are also a major focus at the CAMK PAN. Sophisticated GRRMHD simulations (magnetohydrodynamics in general relativity with the inclusion of radiation) are being carried out on supercomputers. Recently obtained results have called into question the paradigm of thin and thick accretion disks, and a new model (puffy disks) of the structure of stable accretion disks of nearly Eddington luminosity has been worked out. According to the GRRMHD simulations performed in collaboration with the Silesian University in Opava and Harvard University, such luminous accretion disks around black holes combine features of both geometrically thin disks (in that most of the accreting fluid is concentrated close to the mid plane of the disk), and of the Polish Doughnuts (in that the observable surface of the disk forms a funnel-like structure through which radiation escapes).



>> Fig. 1: ULXs in M51 (the Cartwheel Galaxy) are visible as bright spots (encircled in red) in the spiral arms.
Image credit: NASA.

**Marek Sikora**

# Relativistic jets

Accretion of matter onto compact astrophysical objects is often accompanied by the production of narrow streams of magnetized matter called jets. The most spectacular and best studied are those associated with radiogalaxies and 'radio-loud' quasars, objects where the central activity is powered by accretion onto supermassive black holes.

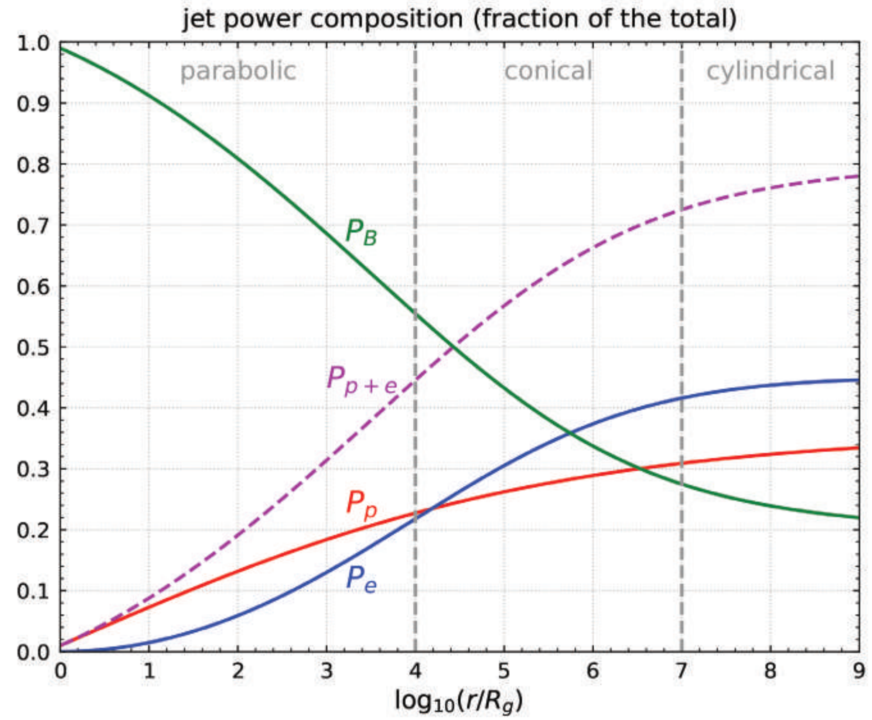
Their matter streams, with relativistic speeds corresponding to a Lorentz factor in the range 3-30, have powers sometimes approaching or even exceeding the accretion power, and extend up to distances billions of times larger than the size of the region where they are launched. Such jets are most likely powered by rotating supermassive BHs immersed in the magnetic fields confined by accretion flows.

Matter in such jets is very rarified, so the plasma is collisionless, and production of radiation is dominated by ultrarelativistic particles via the synchrotron mechanism and the inverse-Compton process. The resulting electromagnetic spectra extend from very low radio frequencies up to high-energy gamma-ray bands. However radiation produced by relativistic jets is strongly beamed in its propagation direction, and can be observed only from objects with jets oriented close to the line of sight. The class of active galactic nuclei with such a jet orientation is represented by the so called blazars. Their multi-band spectra and variabilities provide data which allow to explore the physics of jets on sub-parsec and parsec scales. Such studies are actively conducted in CAMK PAN and cover the following issues: radiation mechanisms, particle acceleration processes; dissipative processes (shocks and magnetic reconnection), magnetization, matter composition of the jet plasma (leptonic component vs. barionic component), jet speeds and powers. Some of these subjects are also covered in section "Magnetic dissipation in relativistic jets".

At CAMK PAN the physics of relativistic jets is also studied on much larger scales than those associated with the blazar phenomenon. Such studies are based on the observations of radio cores on the scales of tens of parsecs, bright knots on the kiloparsec scales and giant radio-lobes, inflated by jets, that extend up to hundreds of kiloparsecs. Combining them together allowed us to estimate the electron-positron pair content and the contribution of pairs to the total energy flux as a function of distance from the central black hole. Preliminary results are illustrated in Fig. 1.

Our interest in the extragalactic jets is not limited just to their physical structure. Luminous double radio structures powered by jets are observed only around a few percent of quasars. This implies that the conditions required to produce powerful jets must be quite exceptional. If strong relativistic jets are powered by the Blandford-Znajek mechanism, their powers should scale with the square of the BH spin and the square of the magnetic flux threading the BH. While the BH spin is determined by the cosmological evolution of the black hole, the amount of magnetic flux supported by external currents and confined onto the black hole by the accretion flows depends on the structure and evolution of the innermost portions of the latter. As theoretical models and their numerical simulations predict, the maximal black hole magnetic flux is limited by the ram pressure of matter infalling onto the BH, and is maximized in the case of geometrically thick accretion flows. In such a case, accretion in the innermost regions is blocked by magnetic fields threading the BH, and the so-called magnetically-arrested-disk (MAD) is formed. Jets produced by the Blandford-Znajek mechanism in such a configuration by rapidly rotating black holes may reach powers comparable to the accretion powers and sufficient to explain the energetics of the most luminous radio-sources.

It remains unknown why jets are produced efficiently only in a small fraction of active galactic nuclei. The simplest answer could be that in most AGN the BH spins are very small. However, studies of the cosmological history of the radiation of quasars, and of the BH mass resulting from the accretion process, indicate that the average BH spin should be high even in the radio-quiet quasars. This implies that the broad range of the jet production efficiencies cannot be explained by BH spins, but rather by the magnetic fluxes threading the BHs. Two main scenarios have been proposed to explain the origin of large BH magnetic fluxes: (1) that the accumulation of BH magnetic flux proceeds during the quasar phase, or (2) that net magnetic flux is advected to the BH by a hot quasi-spherical accretion flow prior to the triggering of the quasar phase. Such investigations have been performed at the CAMK PAN over several years as part of an international collaboration, and they partially overlap with the studies of jet production in X-ray binaries.



>> Fig. 1: Our proposed model of the composition of the power of relativistic jets as a function of distance from the central black hole (in units of the black hole gravitational radius $R_g$): $P_B$ is the relative contribution of magnetic fields, $P_p$ is the relative contribution of protons, $P_e$ is the relative contribution of leptons (electron-positron pairs). We indicate the three main geometric jet zones: parabolic at subparsec scales, conical at galactic scales and cylindrical at extragalactic scales. Emission from blazars is produced roughly at the end of the parabolic zone.

Image credit: K. Nalewajko.

**Krzysztof Nalewajko**

# Magnetic dissipation in relativistic jets

Active galaxies often produce powerful collimated outflows ("jets") which protrude from their centers and extend far into the intergalactic space, to distances as large as megaparsecs. The mechanisms underlying jet launch and acceleration are one of the hottest topics of astrophysical research.

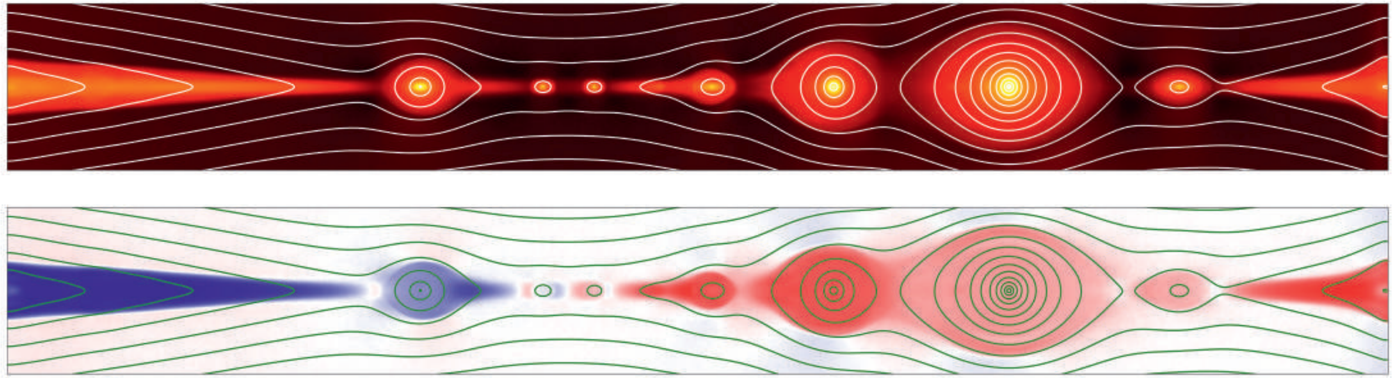
When observed with high resolution radio interferometers, these jets routinely show apparently superluminal motions ($v_{app} > c$, where $c$ is the speed of light in vacuum), which means that their real velocities – while subluminal – are very close to $c$, and hence relativistic. When such a relativistic jet is oriented towards the observer, it appears as a blazar – an extremely bright and strongly variable source of broadband non-thermal radiation, observed across the whole electromagnetic spectrum from radio waves to TeV-energy gamma rays. Explaining the observed emission of blazars requires a very efficient mechanism for energization of jet particles. The current paradigm for the formation of jets and their acceleration to relativistic velocities predicts that jets are initially dominated by magnetic fields, in the sense that magnetic energy density exceeds even the rest-mass energy density of all particles. In such an extreme environment – inaccessible in laboratories and without an analogy in the Solar System – this becomes a theoretical problem of magnetic dissipation.

A basic mechanism for local conversion of magnetic energy into thermal and/or kinetic energy of particles – magnetic reconnection – has been originally proposed to explain the solar flares. Another important example of reconnection in the Solar System – accessible for direct measurements by satellites – is found in the interaction between the Earth's magnetosphere and the solar wind. Magnetic reconnection can occur wherever the magnetic field lines are locally inverted. However, the plasmas found in the Solar System are not magnetically dominated in the sense mentioned above, and hence they are not relativistic. Thus, the relativistic magnetic reconnection must be investigated by means of numerical simulations.

At CAMK PAN, kinetic numerical simulations of relativistic magnetic reconnection have been performed by my group since 2015. We use the numerical code *Zeltron* based on the particle-in-cell (PIC) algorithm, developed by Dr. Benoit Cerutti at the University of Colorado in Boulder. Small-scale simulations are performed on the local cluster (see chapter Computing Facilities). Large simulations are executed on the *Prometheus* supercomputer located in the ACK/Cyfronet computing centre in Kraków, which is currently the largest supercomputer in Poland. *Prometheus* allows us to perform 3D PIC simulations on a computational grid of $1152^3$ cells with the total of 24 billion particles, which is essential for obtaining competitive results.

In our numerical investigations we explore a variety of initial configurations. The most common approach is to simulate a 1D equilibrium that involves a pre-defined current layer (called Harris layer), in which the reconnection is triggered spontaneously due to the development of a tearing mode instability. We have also pioneered an alternative 2D or 3D equilibrium that involves smooth magnetostatic waves, the so called ABC magnetic fields. Our simulations can be performed either in 2D or in 3D, and we are able to include the effect of radiation reaction (synchrotron or inverse Compton mechanism) applied to every particle at every time step. This allows us to calculate accurate radiative signatures of particles accelerated at reconnection sites.

The figure presents an example from the recent results obtained by CAMK PAN Ph.D. student José Ortuño Macías. They show a cropped snapshot from a 2D simulation initiated from a horizontal Harris layer and conduced using open boundary conditions (left/right wall of the computational domain).



>> Fig. 1: Top – energy density of the plasma shown on a logarithmic scale (increasing from dark brown to bright yellow). Bottom – horizontal velocity of the plasma, with blue regions moving to the left, and red regions moving to the right. Green curves are magnetic field lines. Closed lines are signatures of plasmoids – dense compact structures generated by tearing modes of the plasma. In this case, an active site of magnetic reconnection is located between the blue and red velocity regions. The reconnection accelerates a significant fraction of particles to high energies by means of localized electric fields, and it also drives strong outflows ("minijets") which in turn push the plasmoids away from the reconnection site. Plasmoids collect hot plasma from minijets, growing to different sizes. Large plasmoids tend to be slower, and hence they collide with smaller and faster plasmoids. The two largest plasmoids are about to merge, which will promptly result in a rapid flare of radiation beamed towards an observer looking from the right. We proposed that plasmoid collisions can be responsible for the rapid variability of non-thermal radiation observed in many blazars.
Image credit: José Ortuño Macías, Krzysztof Nalewajko

**Andrzej A. Zdziarski, Barbara De Marco**

# Sombreros and lampposts: The geometry of accretion onto black holes

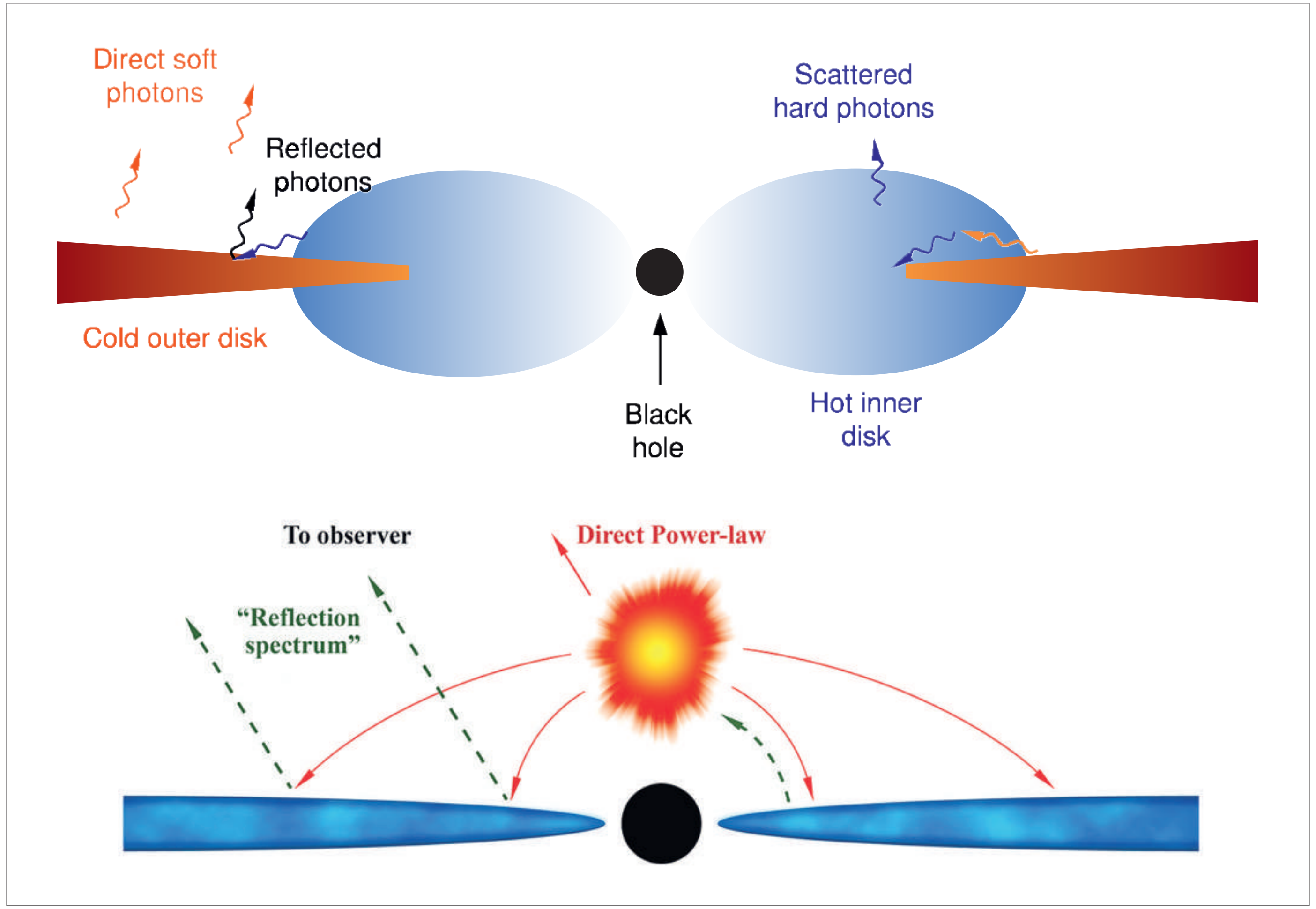
Matter falling (accretion) onto black holes is the most efficient energy generation process occurring in nature. It can release up to 30% of the rest mass energy ($mc^2$), which is 50 times more than can be achieved in thermonuclear reactions, and about 100 million times more than in the most efficient chemical reactions. The endeavour to study it engages many physicists and astronomers around the globe who seek to understand its detailed workings.

We know now two forms in which black holes exist in the Universe: those in stellar binary systems, with masses about ten times higher than that of our Sun, and the supermassive ones in centres of galaxies, with masses ranging from millions to billions Solar masses. The former are final evolutionary stages of massive stars, whereas the latter were probably formed in the early Universe together with galaxies, in a way we still do not fully understand. Black holes are invisible; their gravity is so powerful that any radiation emitted below the horizon is so strongly attracted that it bends back and can never cross the horizon. What we can observe is the accreting matter which heats up upon approaching the horizon, and emits high-energy radiation. Systems in which accretion onto black holes occurs are called X-ray binaries in the case of stellar-mass black holes, and active galactic nuclei in the case of supermassive black holes.

The standard model of accretion onto black holes, developed around the year 1973 by three Russian astrophysicists, Nikolai Shakura, Rashid Sunyaev and Igor Novikov, and the US astrophysicist Kip Thorne, predicts the formation of a disk surrounding the black hole. The radiation of the disk is relatively similar to that of stars, in the sense that a given point of the disk is in local thermodynamical equilibrium and emits a so-called blackbody spectrum. The spectrum of the entire disk is then a sum of local contributions extending from its outer edge (where it has the lowest temperature) to the inner edge (where it achieves the highest temperatures). It turns out that the highest realistic disk temperatures in stellar binary systems correspond to the emission in the soft X-ray photon energy range.

However, this model cannot describe commonly occurring states of accreting black-hole sources in which they emit strong radiation at hard X-ray energies. This spectral component has to be emitted by ionized matter away from thermodynamical equilibrium – a rarefied hot plasma at a characteristic temperature of about billion ($10^9$) Kelvins. The location of this plasma has been the subject of an intense and heated controversy, especially in the case of stellar-mass binaries. Two main scenarios have been proposed:

The accretion disk evaporates far away from the black hole and changes into hard X-ray emitting plasma. Thus, a sombrero-like structure is formed, as illustrated in Fig. 1 (top panel).



>> Fig. 1: Schematic views of proposed plasma flow geometries around accreting black holes emitting hard X-rays. Top: the outer accretion disk evaporates at some distance from the black hole, and transforms into a hot inner flow emitting hard X-rays forming a "sombrero". Bottom: the accretion disk extends to the innermost stable orbit around the black hole,. The hard X-ray source of a "lamppost" type is located close to the black hole.

The accretion disk extends down to the minimum possible radius around the black hole (which corresponds to the innermost stable circular orbit), while the hot plasma is located somewhere close to the horizon, forming a 'lamppost', as illustrated Fig. 1 (bottom panel).

The first scenario explains most of the existing observations, and is in agreement with hot accretion models developed since the 90s. The main argument for the second scenario is given by observations of broad emission lines of iron (from L→K radiative atomic transitions; at 6.4 keV for neutral iron), The broadening is explained by extreme relativistic effects, which in turn require the X-ray source to be located very close to the black hole horizon. At CAMK PAN we have put a lot of effort into resolving this controversy in the case of stellar-mass black holes. We have used a number of methods.

First, we studied the observed spectra with iron lines. In the case of the binary system GX 339-4, we found that the lines are actually much narrower than those claimed before, and in one case the differences were explained by instrumental effects in X-ray detectors, not properly taken into account earlier. In another piece of work, we found problems with the physical self-consistency of the previously used models. In the case of the binary system Cygnus X-1, we found that the continuum spectrum on which the line is superimposed has a more complex shape than that assumed earlier, which also causes the line to become much narrower. In all cases, we found that the accretion disk appears to be truncated far away from the black hole.

Secondly, we studied physical effects taking place when the X-ray source is located close to the horizon of a black hole, and is surrounded by an accretion disk extending to the innermost stable circular orbit. Close to the horizon, gravity is so powerful that it strongly bends the light, which causes most of the emitted radiation to fall into the black hole instead of propagating outside. This effect is in conflict with many observations. We also found that production of electron-positron pairs in photon-photon collisions within the hard X-ray source is so fast that its rate greatly exceeds that of pair annihilation. Thus, such a situation cannot be sustained for a prolonged time, again in conflict with observations.

Thirdly, we studied time delays between photons observed at different energies. Such delays can occur when hard photons hit the disk, and are absorbed and then re-emitted as soft photons with lower energies. We have shown so far that the observed delays of the soft photons with respect to the hard ones are quite long in the case of a few sources, in agreement with the geometry of a disk truncated at a large radius.

Fourthly, we considered the re-emission of the flux impacting the disk. The incident flux is partly back-scattered via the Compton process, and partly absorbed in the disk, and then re-emitted after undergoing atomic processes. The two kinds of re-emission occur in approximate equipartition. The form of the flux re-emitted after absorption, $F_{abs}$, is limited by the Stefan-Boltzmann law. Namely, the lowest energies at which it can be re-emitted are those of the blackbody spectrum at the effective temperature, $T_{eff}$, given by $F_{abs} = \sigma T_{eff}^{4}$, where $\sigma$ is the Stefan-Boltzmann constant. This corresponds to the full thermodynamical equilibrium, which is generally not achieved in accretion disks. We find that for stellar-mass black-hole systems in high-luminosity, hard X-ray emitting states and the full disk geometry (Fig. 1, bottom panel), the effective temperature is $kT_{eff} > 1$ keV, where $k$ is the Boltzmann constant. This would imply the presence of strong quasi-thermal spectral features at several keV, which are not observed at all in the hard X-ray emitting states. This is a powerful constraint, ruling out the full disk geometry in high-luminosity hard states, and thus it has fundamental implications for theoretical models of accretion.

One of us (AAZ) together with Prof. Tomaso Belloni from INAF (Italy) applied for a grant to organize so-called Team Meetings at the International Space Science Institute in Bern, Switzerland, during which a group of 12 internationally renowned scientists and 3 students meet for two week-long discussions (separated by about a year) devoted to a highly interesting astrophysical topic. The proposal to discuss the geometry of accreting black holes, with the same title as this article, was accepted, and the first meeting took place in January 2020. Representatives of the two opposing points of view spent that week in intense discussions. Unfortunately, no consensus has been achieved yet, and both sides have kept their former convictions.

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**Alex Markowitz**

# Compact sources: timing and spectroscopy

Our group at CAMK PAN investigates the nature of accreting supermassive black holes --- Active Galactic Nuclei (AGN). As most AGN are typically too distant and too compact for us to image the inner accretion disk, we rely on spectroscopy and continuum timing to infer the geometry and physics of accreting matter in AGN, and to draw parallels between accretion characteristics of AGN and stellar-mass Black Hole X-Ray Binaries (BH XRBS).

### Timing studies, including period searches

Quasi- or strictly-sinusodial periodic signals can originate in the inner accretion disk which directly feeds the black hole, thus probing disk properties and black hole spin. Such signals are routinely detected in BH XRBs and in various stellar systems, but are trickier to detect in AGN. There are some claims of periodic signals in AGN in the literature, attributed to binary supermassive black hole systems --- a source of gravitational wave emission --- or jet precession. However, the continuum emission of AGN is dominated by aperiodic stochastic fluctuations („red noise”), whose low-frequency, large-amplitude trends can spuriously mimic few-cycle sinuosoids and thus potentially trick researchers into making a false claim of a periodic signal.

Our group is currently developing guidelines on the proper use of certain statistical methods commonly used to search for (deterministic) periodic signals in (red-noise-dominated) AGN light curves. Such guidance is necessary because astronomy is entering the era of „Big Data” --- large current and near-future ground-based observing programmes (e.g., PanSTARRS, PTF, ZTF, LOFAR, LSST) monitor or will soon monitor large fractions of the sky, producing light curve databases that allow period searches over thousands to millions of AGN. Claims of multiple periodic signals from such database „trawls” have already been made, but most period claims are likely the product of red noise, with improperly-calibrated false alarm probabilities.

Our goal is to guide the community in producing only statistically-significant period claims, and thus constructively impact the assessment of various interpretations of periodic signals in AGN, e.g., the fraction of galaxies hosting binary supermassive black holes, or the fraction of radio-loud AGN with precessing jets.

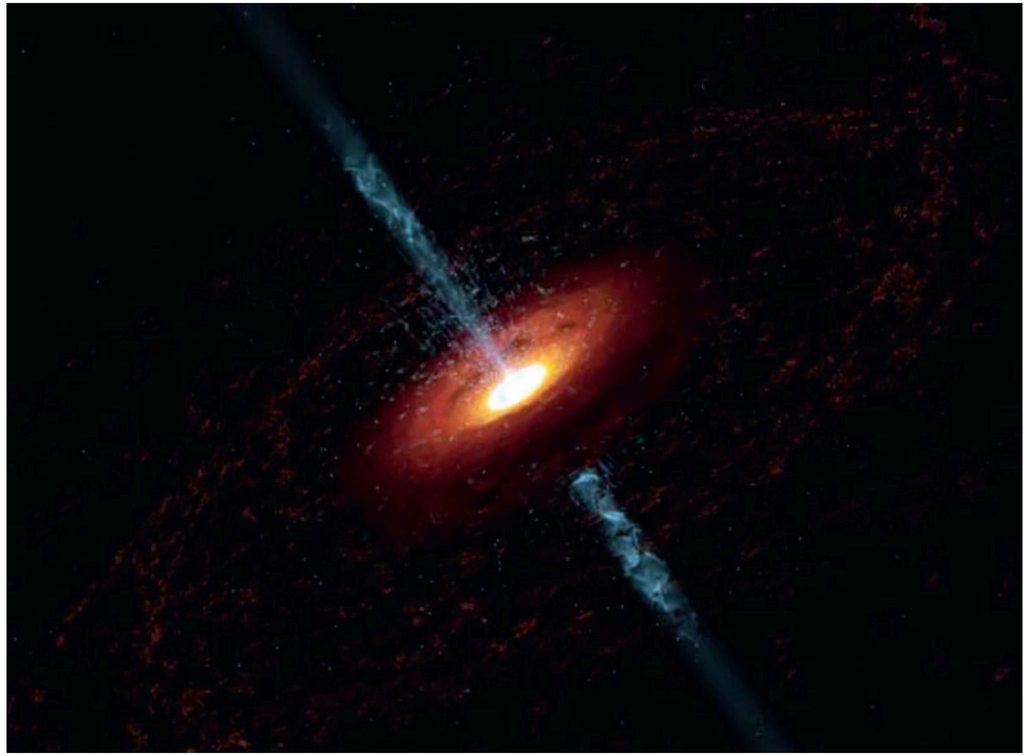
Other projects focus on using timing methods to discern the structure and properties of accreting to outflowing gas. We measure power spectra density functions to test scaling between Seyferts and black hole X-ray Binaries in terms of their accretion properties. We also measure X-ray/optical interband correlations in radio-quiet Seyferts to map the temperature profile of accretion disks, and interband correlations in radio-loud AGN to discern the sizes and content of the emission regions in their relativistically-outflowing jets.

### X-ray Spectroscopy

We also perform X-ray spectroscopic measurements on nearby AGN to infer the exact distribution of accreting matter, in particular the dusty „torus"; this component has been invoked to explain ranges in observed multi-band properties across AGN, such as the level of X-ray obscuration, or optical spectral properties. Our goals are to determine if the torus is composed of solid or clumpy structures (or both), and to determine the torus radial and angular extent.

We can trace the geometry and densities of circumnuclear gas structures that transit our line of sight to the central X-ray-emitting corona near the black hole and temporarily absorb those X-rays. We can then determine the sizes of individual clumps as well as their locations and volume-filling factors; clouds discovered so far are typically light-hours to light-days in size, and their locations span distances commensurate with the optical Broad Line Region to the inner region of the dusty torus. Such observational constraints can provide tests for new, clumpy-torus models, which posit distributions of clouds comprising circumnuclear gas, and also provide physical insight into why some matter becomes clumpy. Our observations also complement infrared spectral and interferometric observations of clumpy tori in the inner parsecs of AGN.

Our X-ray spectroscopic studies also explore characteristics of accretion disks, outflowing winds, and/or jet emission e.g., in Centaurus A, the nearest radio-loud AGN. We frequently use most major current X-ray missions to collect data, e.g., XMM-Newton, AstroSAT, and NuSTAR, as well as use archival data from past X-ray missions, such as Suzaku and the Rossi X-ray Timing Explorer, and we study both individual interesting targets as well as small samples of AGN.



>> Fig. 1: Artist's illustration of a somewhat-clumpy torus; determining the exact morphology of accreting circumnuclear gas across AGN is one of our group's goals.
Image credit: NRAO/AUI/NSF.

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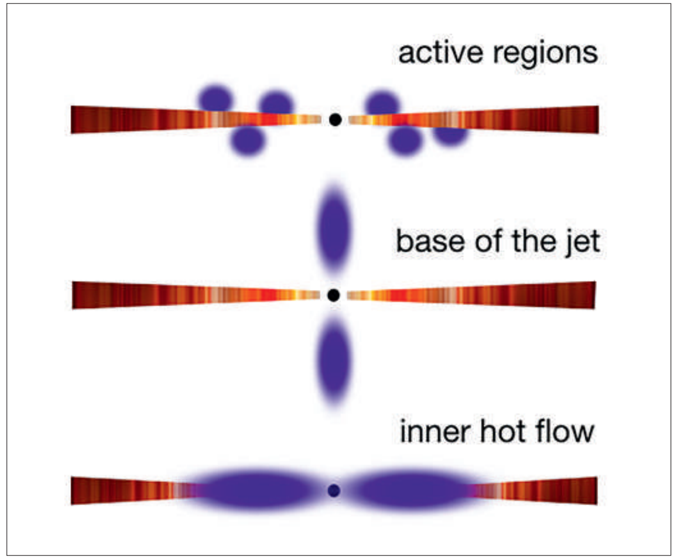
**Barbara De Marco**

# An X-ray spectral-timing view of accreting black holes

Accretion onto a black hole (BH) releases enormous amounts of high-energy quanta, but the details of this fascinating process are poorly known. The method of X-ray spectral timing allows to constrain the physics and the geometrical structure of emitting regions both in galactic X-ray binary systems (BHXRB) and active galactic nuclei (AGN).

BH accreting systems emit copious X-ray radiation. This radiation is produced in the inner regions of the accretion flow, via inverse Compton scattering of thermal photons generated in the accretion process. Unfortunately, the exact location (whether on the BH axis or above the disk) and spatial distribution (whether compact or radially/vertically extended) of the X-ray source is unknown. Moreover, the structure of the standard, optically thick and geometrically thin accretion disk may change in the vicinity of the source (the disk may be truncated or shredded). As a result, little is known about the physical properties of the gas in BH surroundings, and we lack crucial data needed to understand the formation of powerful jets. Fortunately, the central hard X-ray source irradiates the colder gas in the disk which can reprocess a large fraction of the incident radiation, producing a complex spectrum. In AGN, reprocessing is also seen to occur on scales much larger than the disk, e. g. in the so-called broad line region (BLR). Thanks to this reprocessed radiation we may indirectly study the structure of the disk, and the gas surrounding the X-ray source.

One of the defining properties of both BHXRB and AGN is the strong and rapid variability of the X-ray radiation they emit. In our studies we use this variability as a tool to constrain the physical properties of the gas in the close environment of the BH. The fastest variability is, indeed, produced in the innermost accretion flow, thus carrying valuable information about these regions. In particular, a variable X-ray signal impinging on the surrounding gas will result smeared and time-delayed as



>> Fig. 1: Some of the geometries proposed for the accretion disk (reddish structure) and the X-ray source (blue structure) in accreting BH systems.

a consequence of the finite light travel time between the X-ray source and the reprocessing region. This so-called X-ray reverberation signal can be used to map the geometry of the inner accretion flow. In order to study this kind of signal we need to separate the contribution of different spectral components to the variability observed on different time scales, pinpoint those produced in the innermost regions, and study their causal relationship. Currently the best approach to achieve these goals is based on "spectral-timing" – a suite of Fourier-domain techniques which allow to extract spectral and timing information on the time scales of interest.

At CAMK PAN we make extensive use of these techniques for the study of both BHXRB and AGN. For our analyses we utilize the best X-ray data currently available, obtained from X-ray detectors characterized by large collecting power and optimal timing capabilities. These include the detectors onboard XMM-Newton and NuSTAR telescopes, and the NICER payload onboard the International Space Station.

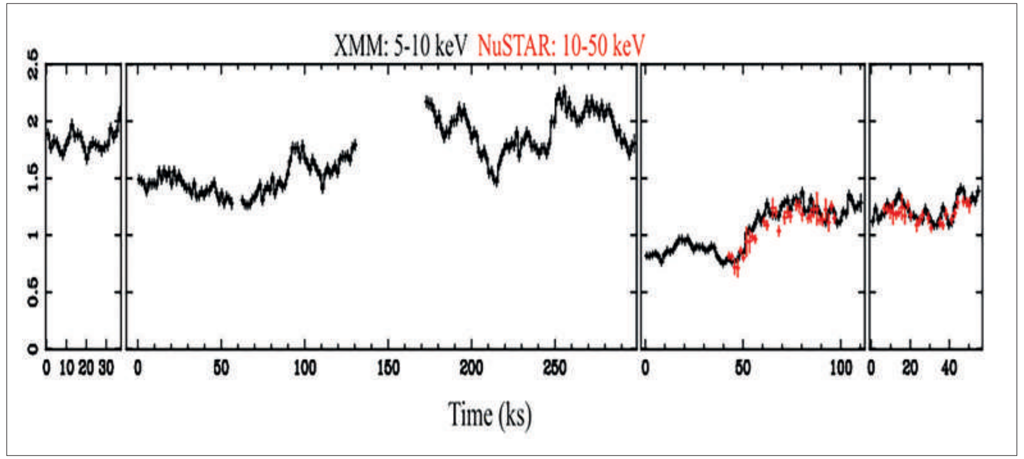
Our X-ray spectral-timing studies of BHXRB are aimed at resolving the evolving structure of the inner accretion flow as a function of the accretion state of the source during an outburst of activity. In particular, we are interested in:

- understanding how the inner truncation radius of the standard disk evolves, particularly when the source is close to the transition between hard and soft states
- constraining the geometry of the Comptonizing region, as well as its spectral distribution
- investigating how the X-ray spectral-timing properties of BHXRB in different accretion states scale to those observed in different types of AGN.

Finally, in collaboration with other research groups in the UK and in Italy, we investigate the coupling between accretion and ejection processes by studying how the fast X-ray variability originating in the accretion flow correlates with the fast IR variability, possibly associated with the jet.

Our X-ray spectral-timing studies of AGN are aimed at:

- constraining the geometry of the disk and the X-ray source in AGN of different classes
- understanding whether this geometry is stationary or changes over time, e. g. when the source experiences large variations of the X-ray flux
- understanding the origin of the excess of soft X-ray emission seen in many type 1 AGN (the so-called "soft excess"), and whether this is associated with intrinsic and/or reprocessed emission in the disk
- employing X-ray spectral-timing techniques to study X-ray outflows in AGN (in particular – to constrain the density and location of the outflowing gas), as well as to characterize their influence on intrinsic X-ray spectral-timing properties of the source.



>> Fig. 2: The rapidly variable X-ray flux from the Seyfert 1 galaxy NGC 3783, as registered by detectors onboard XMM-Newton (black) and NuSTAR (red) during four different observations.

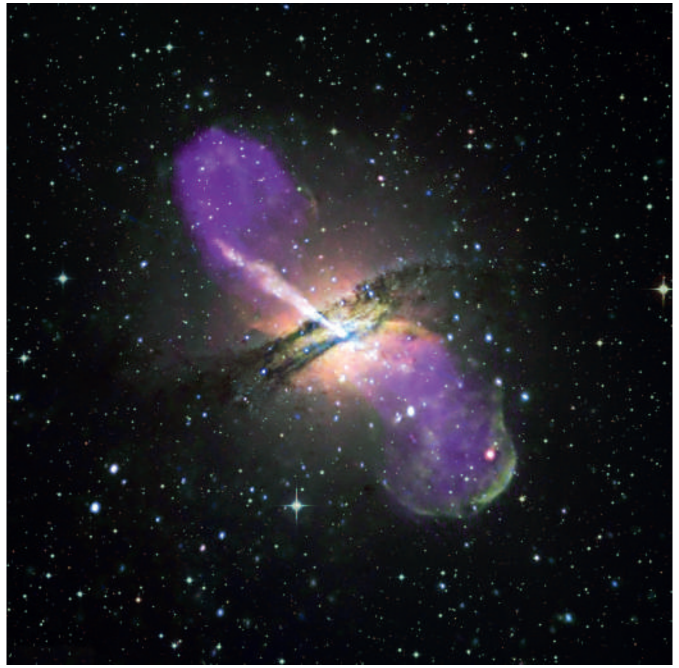
**Agata Różańska**

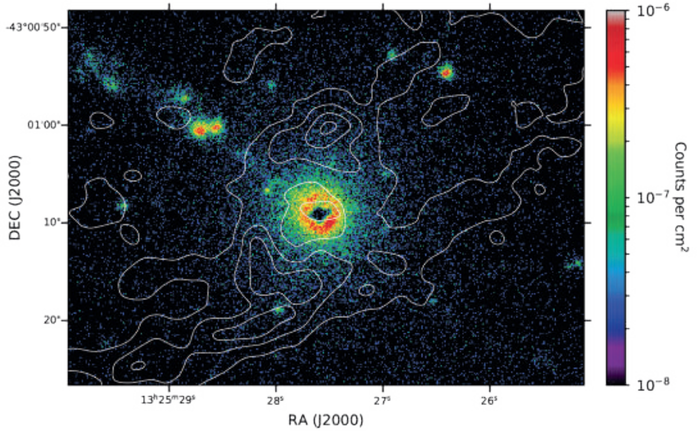
# X-ray spectroscopy

Almost 50% of ordinary (baryonic) matter in the Universe is locked in the so called hot phase, heated up to several millions of degrees kelvin. How this gas became so hot and how it influences today's Universe large scale structure and dynamics – these are some of the main questions of X-ray astronomy.

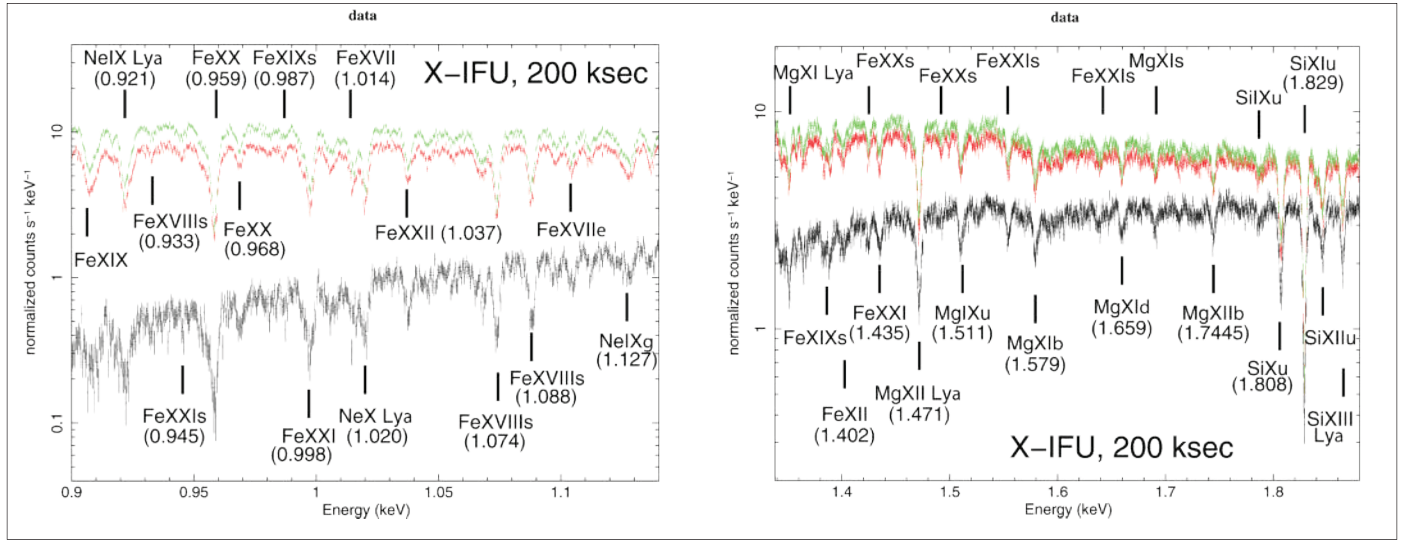
X-ray astrophysics is an already well established and fast developing branch of modern astronomy. We have been observing the Universe in X-rays for almost 70 years, from the time we learned how to build X-ray telescopes and put them into space, opening the domain of High Energy Astrophysics.

In CAMK PAN, our group works on observations and modelling in the X-ray domain. We mostly use *Chandra* archival images of the hot gas around supermassive black holes to understand the structure of this elusive medium, and to determine its physical parameters. The regions of particular interest are those where we see hot





>> Fig. 1: Left: Centaurus A galaxy in different wavelengths. The X-ray jet is seen as a white ray inclined to the dark dusty band seen in optical/infrared observations. Right: A combined *Chandra* (color map) and ALMA (contours) image of the central part of Centaurus A, where we clearly see the interplay of hot and cold gas.
Image credit: NASA, CXC, NSF, VLA, ESO (left); A. Różańska and coauthors (right)



>> Fig. 2: Simulated data for an exposure time of 200 ksec, calculated for three different column densities of the interstellar gas responsible for the Galactic absorption. Black, red and green colours represent column densities $N_H = 10^{22}$, $10^{21}$, and $10^{20}$ particles per $cm^2$, respectively. We show regions around Lyman α lines of neon (left) and magnesium (right).
Image credit: A. Różańska and coauthors.

gas together with cool matter observed with visible or infrared instruments.

We are developing models which explain why those two phases of gas, cold and hot, do not mix in the vicinity of a black hole. An important physical mechanism responsible for the coexistence of two phases differing in temperature by four orders of magnitude is the thermal instability caused by strong radiation fields. In the case of Sagittarius A* (a supermassive black hole at the center of our Galaxy) we have shown that when its broad-band radiation is taken into account, it is possible to reproduce the radial distribution of the hot plasma.

In addition to the most accurate, spatially resolved images made by the *Chandra* mission, we work with spectroscopic data from currently operating X-ray telescopes, like XMM-Newton, NuSTAR, *MAXI*, INTEGRAL, NICER, *AstroSat*, and eROSITA. Thanks to X-ray spectrometers we measure the energy flux carried by photons of a given frequency that fall into detectors. Spectroscopic data are crucial for each energy band, but especially for X-rays, as only due to them we can learn about physical processes responsible for hot gas emission.

For many years we have been performing radiative transfer computations of hot atmospheres in different sources. We model atmospheres of illuminated accretion disks in active galactic nuclei (AGN), hot accretion disks in black hole binaries, warm coronae above accretion disks, neutron star atmospheres, and transmission of radiation through the diluted ionized media like "warm absorbers" in or outflows from AGN. In all cases advanced numerical computations are performed, which couple the radiative transfer solution with the solution for the gas structure. All radiative processes are fully taken into account including Compton scattering on electrons with relativistic velocities. We always aim to compute gas in thermal and ionization equilibrium.

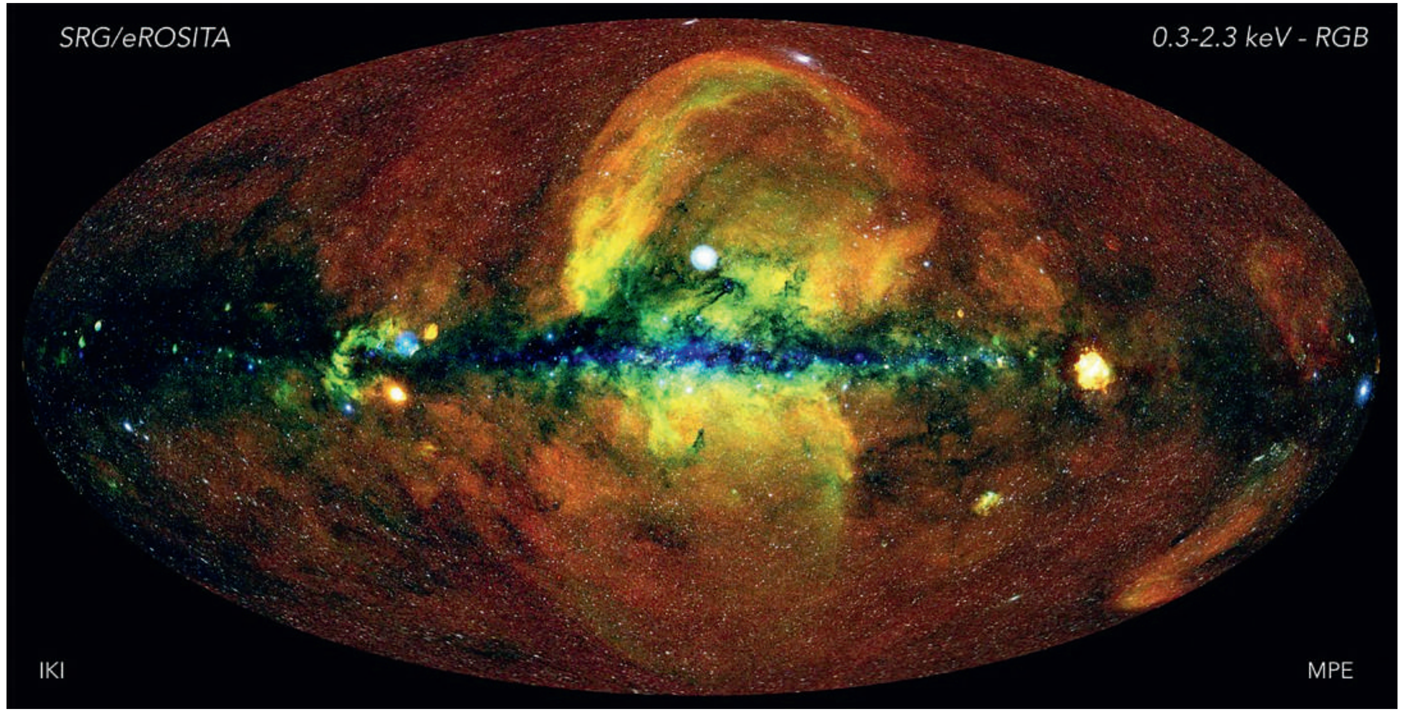
We find that the reflected spectrum should be computed assuming hydrostatic equilibrium of the reflecting medium. Furthermore, we show that the transmitted spectra of warm absorbers are much better reproduced under the assumption of gas at constant total pressure (CTP) than that of gas at constant density. We have demonstrated that CTP clouds can explain high resolution observations of warm absorbers in AGN. We postulate that to reproduce the absorption measure distribution in those sources the gas should be quite dense, of the order of $10^{12}$ particles per $cm^3$.

Continuum emission from neutron star atmospheres allows us to determine the neutron star mass and radius by continuum fitting method. Our advanced models are currently computed for different chemical compositions, and they can be directly compared with observations.

Ionized outflows are observed in different objects, starting from clusters of galaxies through central parts of single galaxies to AGN. The outflowing gas is visible due to many X-ray absorption or emission lines detected in high resolution data from those objects. Since these lines are signatures of highly ionized heavy elements, X-ray spectroscopy provides important information about the chemical enrichment. At the same time, it allows us to measure temperature, density and velocity of the gas. The last parameter, the velocity, is particularly important, as it enables us to assess the role of turbulence in heating mechanisms of the intra-cluster plasma.

Our model spectra predict signals which will be detected by future X-ray missions like ATHENA, eXTP, XRISM, Lynx, or ARCUS. On the previous page, we show the model spectrum of absorbed gas as it will be observed by the high resolution X-ray Integral Field Unit – a detector on the ATHENA telescope (see chapter "ATHENA – Advanced Telescope for High ENergy Astrophysics").

Team members: Bartosz Bełdycki, Dominik Gronkiewicz, Samaresh Mondal, Agata Różańska (head).



The X-ray sky mapped in 2020 by the German/Russian satellite eROSITA.

**Tomasz Bulik**

# AstroCeNT and particle astrophysics

Most of the content of the Universe is still invisible to us due to its exceedingly feeble interactions with the ordinary matter that our detectors are made of. The historical discovery of gravitational waves in 2015 provided us with another example that a key to shed light on the invisible Universe is to construct detectors that will be sufficiently sensitive to detect what was previously beyond reach.

AstroCeNT (Centrum Naukowo-Technologiczne Astrofizyki Cząstek; Particle Astrophysics Science and Technology Centre), was initiated by Prof. Leszek Roszkowski and the author to conduct research in science and technology in the areas of particle astrophysics that deal with exploring the hidden Universe. AstroCeNT's two main physics themes are dark matter in the Universe and gravitational waves.

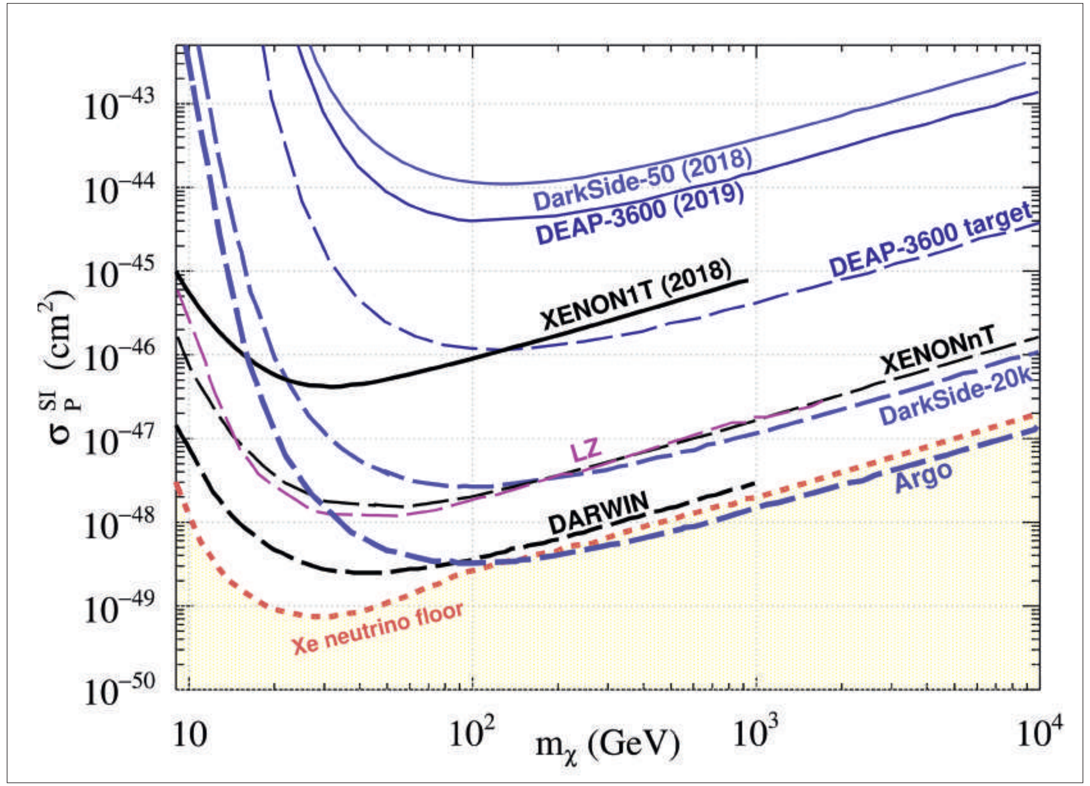
### Dark Matter

There is a wide range of evidence from astronomical observations which indicates the existence of non-luminous, non-baryonic matter, commonly known as Dark Matter. No particle in the Standard Model satisfies these astrophysical and cosmological observations. As of yet, no such particle has been detected in the laboratory. The dark matter puzzle is an indisputable proof of the existence of unknown physics beyond the Standard Model. Many supersymmetric and non-supersymmetric extensions to the Standard Model have natural dark matter candidates. There is a real potential for a groundbreaking discovery below the current detection limits. One of the most theoretically motivated and experimentally accessible dark matter candidates is a weakly interacting massive particle (WIMP), thought to be a thermal relic of the Big Bang, which explains its current abundance in the universe.

Direct experimental WIMP searches typically rely on the process of scattering of dark matter particles on ordinary matter nuclei, in which the recoil energy induces observable effects in the target, e.g. flashes of light (scintillation), ionization or temperature changes. The direct detection of WIMPs is a battle against background events, mainly caused by natural sources of radiation mimicking signals from WIMPs. Detectors are operated deep underground in order to shield the cosmic radiation, and are built from ultra-radiopure materials.

Liquid argon has been proven to be an excellent target for WIMP detection with its good scintillation yield and strong background rejection capability. Additionally, argon extracted from underground sources reduces the level of the internal background, $^{39}$Ar, by a factor of more than 1400.

As a part of the Global Argon Dark Matter Collaboration (GADMC), which unifies scientists from the Ar-based dark matter experiments: DarkSide, DEAP, ArDM and MiniCLEAN, we participate in the operations of DEAP-3600 at SNOLAB (Sudbury, Canada), the currently most sensitive liquid Ar based detector, as well as in the construction of the DarkSide-20k detector with up to 50 tonnes of Ar at Laboratori Nazionali del Gran Sasso in Italy. When operating in background-free mode (targeting < 0.1 background events in 200 t-yr exposure), the DarkSide-20k detector is expected to have 5σ discovery sensitivity for WIMPs with an electroweak scale mass >100 GeV/c$^2$. Furthermore, building on the results of DarkSide-50, which achieved the leading sensitivity in the low-mass WIMP regime (20 GeV/c$^2$), we plan to build a dedicated experiment for light WIMPs.



>> Fig. 1: 90% C.L. exclusion limits, showing leading results from direct dark matter searches (XENON1T with Xe and DEAP-3600 with Ar target) compared with sensitivities of future xenon (LZ, XENONnT, and DARWIN) and argon (DarkSide-20k and Argo) direct searches in dashed lines. The "Xe neutrino floor" curve represents the limit of direct searches due to Coherent Neutrino Scattering.
Image credit: M. Kuźniak)

The groups at AstroCeNT primarily work on searches for new physics with liquid argon detectors (mainly on the DEAP and DarkSide experiments within GADMC), through optimization and development of light collection and Silicon Photo Multiplier (SiPM) photo-detection systems. Leading particle astrophysics experiments rely on efficient collection and detection of scintillation light induced by interactions of these particles with the detector medium, which is achieved with careful optics design and novel reflecting and wavelength shifting materials, and highly efficient sensors.

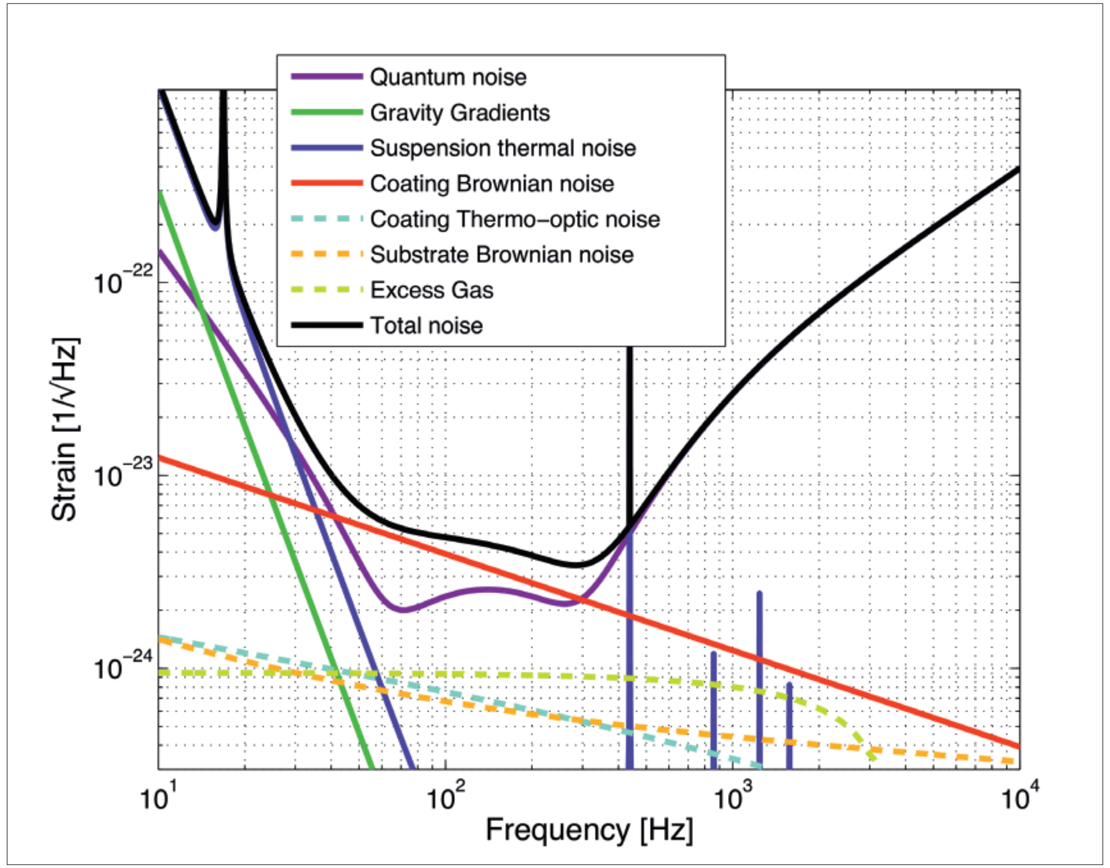
In order to achieve extreme detector sensitivities, the components of the SiPMs based photo-sensors themselves must not generate any background that could potentially obscure the signal from dark matter. SiPMs are a novel cutting-edge technology, which is now being adopted to astroparticle physics experiments. It is widely considered to determine the future of the field, permitting to substitute the vacuum tube detectors known as Photo Multiplier Tubes (PMTs) with much more compact, cheaper, and much more efficient silicon chips, which ultimately translates to improved experimental sensitivity and extended physics reach.

### Gravitational Waves

Gravitational waves have been first detected in 2015 with LIGO. Ever since, LIGO, VIRGO and recently KAGRA continue to search for gravitational waves and have already published 10 detections up to the end of the O2 run. In the current O3 run LIGO and VIRGO provide alerts with the frequency of about once a week. A more detailed review of CAMK PAN participation in VIRGO can be found elsewhere in this book.

Detecting gravitational waves is a constant fight with various kinds of noise. In the high-frequency range, this is primarily quantum noise, connected with the finite number of photons in the interferometer. In the low-frequency part, the main source of the noise is the coupling to the seismic noise in the ground. The seismic noise can couple to the mirror motion in two basic ways. The first is purely mechanical through the rigidity of the towers and suspensions. This coupling can be diminished by the mechanical construction of the suspension. If the suspensions have small enough resonant frequencies then vibrations with frequencies larger than that are quenched. A series of such suspensions can quench the mechanical seismic noise by more than 10 orders of magnitude.

A second, much weaker coupling is through the gravity fluctuations that are induced by the seismic wave field. This type of noise is called Newtonian noise. The seismic waves in the ground or in the floor of the building are changing the height and the density of the floor of the building and therefore introduce small time variations of the gravitational field in the neighborhood of the test mass. Such fluctuations are the cause of the Newtonian noise. An additional source of this noise are infrasonic waves. Sound waves are longitudinal density waves in the air and are clearly a source of gravitational field fluctuations. Currently, the Newtonian noise is not limiting the sensitivity at low frequencies however we believe that in a few years this will be the limiting noise for LIGO, VIRGO, and KAGRA. Newtonian noise will also be important in the future detectors like Einstein Telescope or Cosmic Explorer.



>> Fig. 2: The sensitivity curve of Advanced Virgo. The Newtonian noise is denoted in green as gravity gradient noise Virgo.
Image credit: EGO.

One must add that the sensitivity of the detectors at low frequencies is very important from the astrophysical point of view. First, it will allow to detect more massive black holes. The coalescence frequency is inversely proportional to the mass of the black hole so increasing the sensitivity at low frequencies implies the ability to detect black hole binaries with higher mass. The sensitivity at low frequencies is extremely important for multi-messenger astronomy. Binary neutron stars can be detected up to hours before a merger, if the sensitivity at low frequencies is sufficiently high. This can allow for early localization of the source before the merger, and possible alerts to electromagnetic observatories so that they can point in the direction of the merger when it happens. Such observations will provide a breakthrough in understanding the physics of mergers.

The mitigation of Newtonian noise is not simple. There are no gravity screens, so the only way to quench this type of noise is to detect the underlying cause of the noise — seismic or infrasonic field — and then calculate the resultant gravity gradients, Finally with the model of the field, one can subtract it from the data stream. Thus, the point is to have reliable sensors that can be used to characterize the seismic and infrasonic field in the vicinity of the detectors.

The seismic sensors group at AstroCeNT is working on the development of such sensors with the principal application being gravitational wave detectors. Our activity concentrates on two areas: construction of autonomous seismic sensors, and construction of low-cost infrasonic sensors. The first project involves several sub-projects: low cost autonomous seismic sensor working at frequencies above a few Hz, a mobile platform for seismic sensors, and currently also the use of optical fibers for the construction of large scale seismic sensors. We will use these sensors for the characterization of the Einstein Telescope candidate sites. The second project is a part of the Advanced VIRGO effort. Within this project, we are developing a low-cost infrasound sensor working in the range from 1 to 30 Hz. The sensors will be used for monitoring infrasound noise inside VIRGO buildings as a part of the Polish contribution to Advanced VIRGO.

Additionally, these sensors have a lot of possible applications in industry. In particular, they can be used for monitoring the passage of people and animals, for active seismic sensing in geological and geophysical research, as well as e.g. in archaeology. While our main goal is gravitational wave astronomy, we are also pursuing all these other possible applications of the research on sensors at AstroCeNT.

### Scientific Computing

The development of Near Intermediate Scale Quantum computers and the many successes of machine learning have led to the emergence of the new field of quantum machine learning. Recently, various concepts of quantum neural networks were proposed, and one idea is to employ shallow variational quantum circuits to perform supervised classification. It was already shown that simple classification tasks can be efficiently performed using such shallow quantum circuits. Unfortunately little is known about architecture design for such quantum neural networks, how to mix quantum and classical nodes in such networks, and how to adapt neural network architectures to the existing quantum computer topologies.

The Scientific Computing & Information Technology Group at AstroCeNT, therefore, studies the design of quantum-classical neural networks and investigates their applicability to classification of the data collected by the currently-operating DEAP-3600 experiment and gravitational-wave detectors, LIGO and VIRGO, as well as of simulated data for planned future detectors, such as the DarkSide-20k and the Einstein Telescope.

**Rafał Moderski**

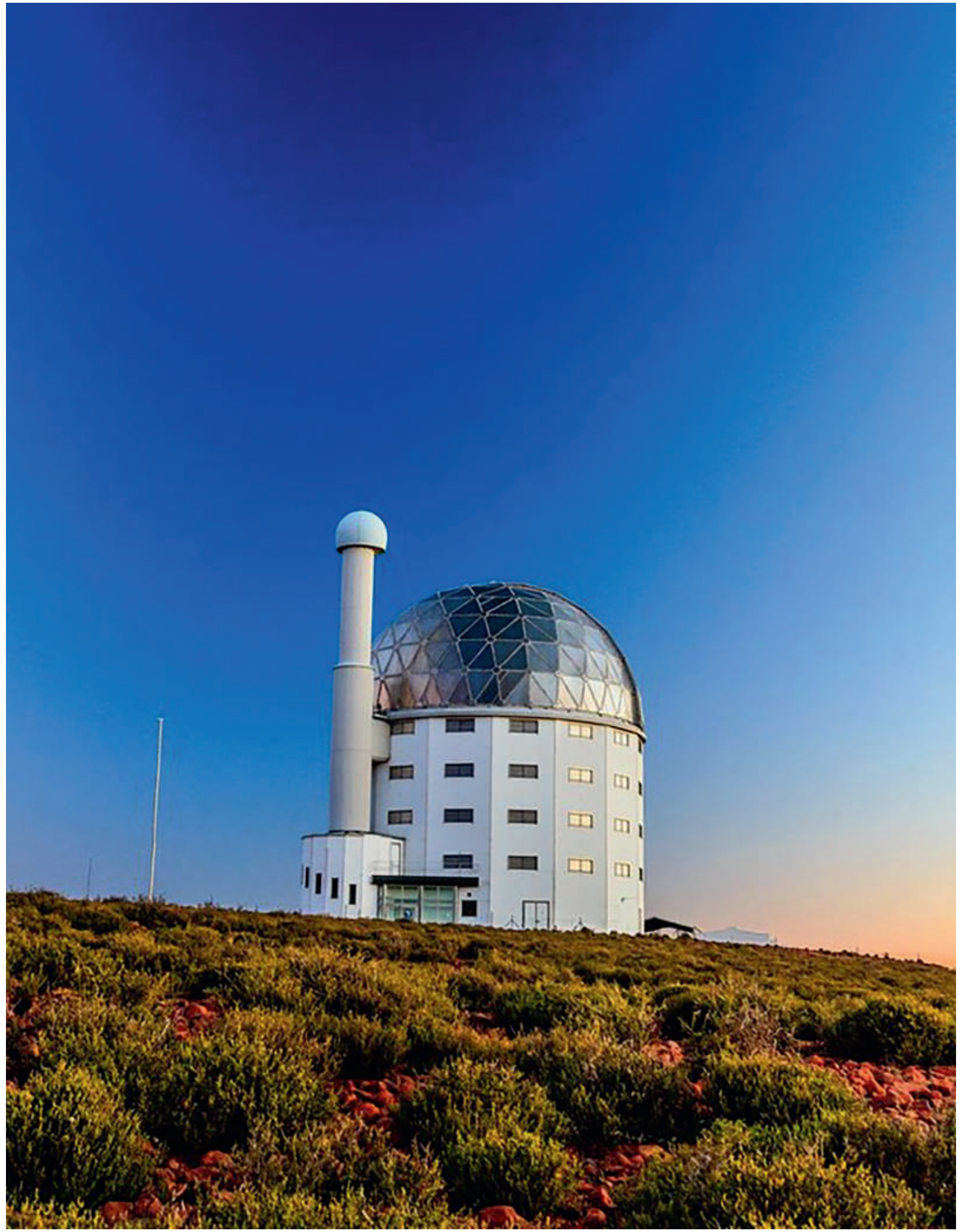
# Ground-based instrumental projects

Nowadays, no astronomer can do research without proper instrumentation. Although spaceborne instruments usually profit from the better view of the skies, Earth-based facilities still remain the core of the research infrastructure also for astronomers. The Nicolaus Copernicus Astronomical Center takes part in many instrumental initiatives around the world.

One of the greatest achievements of scientists at CAMK PAN was to build and operate a global network of small robotic telescopes called SOLARIS (projektsolaris.pl). The project, proposed by prof. Maciej Konacki, consists of four 0.5 m diameter instruments located in the Republic of South Africa (Solaris-1 and -2), Australia (Solaris-3), and Argentina (Solaris-4). The network was originally designed for search for circumbinary planets, but it is now also used in the Space Situational Awareness Programme of the European Union. SOLARIS telescopes search for space debris and determine and predict their orbits. To complete the program an additional, 1 m-class telescope will be constructed at the SOLARIS site in South Africa. This telescope will also work as a testbed for a quantum telecommunication platform - a novel project implemented in cooperation with the Nicolaus Copernicus University in Torun.

South Africa remains a favourite place for Polish astronomers. CAMK PAN plays a role of national coordinator of the Polish involvement in the Southern African Large Telescope (SALT). Poland is one of biggest shareholders in the SALT Foundation Pty (Ltd), represented from the beginning at the SALT board by prof. Marek J. Sarna. SALT telescope is located in South African Astronomical Observatory on Karoo plateau about 370 km north of Cape Town, at an altitude of 1759 m a.s.l. SALT is the largest single optical telescope in the southern hemisphere  and amongst the largest in the world. It has a hexagonal primary mirror array 11 meters across, comprising 91 individual 1m hexagonal mirrors. It is the non-identical twin of the Hobby-Eberly Telescope located at MacDon-

>> Fig. 1: SOLARIS-2 telescope at the Siding Spring Observatory in Australia.
Image credit: M. Konacki.



>> Fig. 2: The Southern African Large Telescope (SALT) in vivid colors.
Image credit: SALT, W. Basson Images

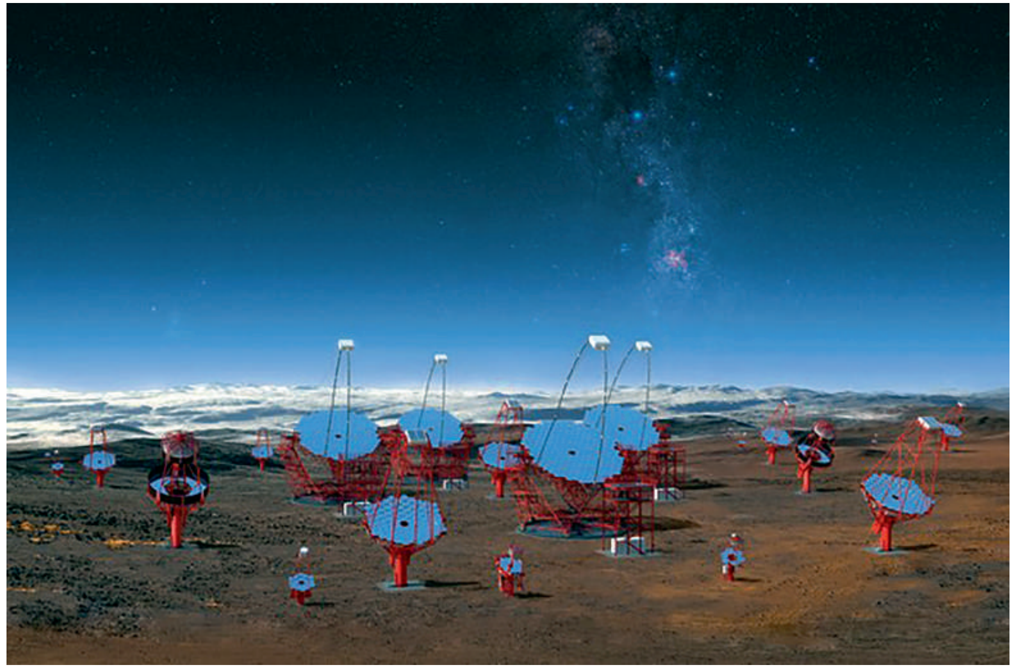
>> Fig. 3: Cerro Armazones Observatory on the slope of the Cerro Murphy mountain in Chile. Image credit: Ruhr-Universität Bochum

ald Observatory. SALT represents a completely new paradigm in the design of optical telescopes. The light gathered by its huge mirror is fed into a suite of instruments (an imager and two spectrographs) from which astronomers infer the properties of planets, stars and galaxies. Several scientific groups at CAMK PAN use SALT for their research, e.g., prof. Joanna Mikołajewska is leading studies of symbiotic stars and novae in the Magellanic Clouds and Milky Way.

The latest addition to the observing capabilities of CAMK PAN is Cerro Armazones Observatory (OCA). This facility, described in details in its dedicated chapter in this book, has been recently acquired from the University of Bohum and it is located in one of the best spots for ground based astronomical observations - Atacama Desert in Chile, about 110 km south of the city of Antofagasta on the slopes of Cerro Armazones mountain. On the adjacent peak the Extremely Large Telescope is currently being constructed by the European Southern Observatory - a really exclusive neighborhood! In April 2020 CAMK PAN signed a contract with Austrian company ASA Astrosysteme to deliver additional telescopes to the OCA observatory. Beside a smaller, 0.8 m telescope, the delivery includes a big 1.5 m class telescope equipped with a 16 Mpix CCD camera - the biggest optical telescope ever operated by the Polish institution. The observatory is dedicated to determine the cosmic distance scale in the course of the Araucaria project lead by prof. Grzegorz Pietrzyński. However the large observational potential of the observatory will allow in the future to coduct several other projects proposed by the Polish astronomical community.

Optical observations are not the only observational domain to gather information about the Universe. My group at CAMK PAN is using the H.E.S.S. observatory to observe the most energetic radiation from the sky - very high energy gamma rays. These photons, with energies billions of times larger than the visible light, are produced in the most violent places: pulsar wind nebula, supernova remnants and active galactic nuclei. H.E.S.S. stands for the High Energy Stereoscopic System and it is an array of five imaging atmospheric Cherenkov telescopes located in the Khomas Highland in Namibia, Africa. These instruments detect Cherenkov radiation from air showers of relativistic particles created in the atmosphere by high energy gamma-ray photons. While four outer telescopes of the H.E.S.S. system are considered medium-sized by the high energy astrophysics standards with their 12 m diameter mirrors, the central telescope is really gigantic - its primary mirror is 28 m in diameter. This is currently the largest mirror on the Earth! CAMK PAN is also the leader of the Polish consortium of scientific institutions participating in the H.E.S.S. Collaboration - a multinational scientific consortium operating the H.E.S.S. array.

Long term cooperation under the H.E.S.S. project has allowed CAMK PAN scientists to actively participate in the construction of the next generation gamma-ray observatory - the Cherenkov Telescope Array (CTA). This will be the largest astronomical observatory ever built. Its southern site in Chile will host almost one hundred telescopes of three different sizes from small, 4 m class to as large as 20 m in diameter. CTA is about to commence its operation in 2022.



>> Fig. 4: Artist impression of the southern site of the Cherenkov Telescope Array.
Image credit: IAC/G. Pérez Diaz, CTAO/ M.-A. Besel

>> Fig. 5: The High Energy Stereoscopic System (H.E.S.S.) observatory in Namibia.
Image credit: H.E.S.S., S. Klepser

**Arkadiusz Olech**

# Polish Fireball Network – the hunt for meteors and meteorites

The research conducted by the Polish Fireball Network (PFN) aims at mapping the layout of fine cosmic matter in close proximity to the Earth, thus identifying meteor swarms and asteroids connected with them which might potentially pose a threat to our planet. At the same time, the project provides more chances to find fresh meteorite falls and transfer them for detailed examination to determine in what conditions our Solar System was born. This, in turn, is closely related to the problem of the origin of life on Earth. It would be difficult to find more fundamental issues.

Despite the fact that the Universe seems to be empty, cosmic catastrophes are happening every second. During 24 hours our planet, moving with a speed of 30 km/s, collides with several million of cosmic dust grains. Most of them are not bigger than an average grain of sand but from time to time something bulkier happens as well. At an altitude of 100 – 120 km the atmosphere is so thick that its atoms crash with cosmic dust approaching the Earth, and they start to shine as a result. When it happens you can observe a "shooting star" in the sky. Astronomers call it a meteor. At the heart of typical meteors, visible with the naked eye, are objects of merely millimeters in diameter. A body as big as your fist might cause an event equally bright as the brightest of planets, Venus (and then we call it a fireball). A body as wide as about a dozen of centimeters can create a meteor as bright as the Moon. The famous Chelyabinsk fireball which shone as brightly as the Sun was caused by a small asteroid, not bigger than 17 meters.

>> Fig. 1: The PFN67 station in Starowa Góra operated by Arkadiusz Raj.
Image credit: A. Raj.

Acquiring cosmic matter has been the aim of many scientists for a very long time. That's why for instance American astronauts went to the Moon and brought back almost 400 kg of rocks. Fortunately we don't always have to fly so far. The Chelyabinsk fireball, and many others as well, showed that sometimes cosmic bodies can literally fall into our hands, it's enough to watch and look for them. What's the use of cosmic matter? It's simply priceless because the age of the oldest meteorites is estimated at 4.6 billion years. It means those rocks, being much older than the oldest rocks found on Earth, 'remember' the beginning of the Solar System! What's more, they can contain noticeable quantities of organic material (including amino acids) which indicates that meteorites, small asteroids and comets might have brought life to a previously barren Earth.

>> Fig. 2: The composite image of Perseids 2016 captured by PFN32 station in Chełm.
Image credit: M. Maciejewski

Statistics indicate that there are a lot of fireballs in our sky but only few of them have any chances of surviving the passage through the atmosphere and finish their flight with the fall of a meteorite. Fireballs such as the one from Chelyabinsk are very few and far between – that one had the luck of being documented with a huge number of camcorders and photographic cameras which then allowed the scientists to analyze it properly, determine its trajectory, orbit and its place of fall. Most of bright fireballs unfortunately pass by unnoticed.

Over the territory of Poland about 100 bright fireballs are visible every year; 2-3 of them have the chance to fall to the ground and end up as meteorites. The majority of them is never found and the statistics are brutal – during the last 25 years there have been only two documented falls of meteorites in Poland (the Sołtmany meteorite in 2011 and the Baszkówka one in 1994).

Still there is a way to register more such events and determine meteorite falls connected to them. Every evening all over Poland cameras belonging to the PFN wake up. A special software checks whether the sky is sufficiently dark, and if the conditions are right, the meteor hunt begins. Almost every bright event within the scope of a given camera is registered and saved on a hard disk. At the same time the computer determines its basic parameters like precise time of occurrence, brightness, angular velocity and trajectory on the sky. The data are then automatically sent to dedicated servers. A specially designed software checks which phenomena were registered by more than one station. If this happens, the data are combined and the meteor reveals all its secrets.

We can determine its trajectory in the atmosphere with a great accuracy, we can find its orbit from before the crash with our planet and then estimate an area of a potential fall of a meteorite if the body is big enough to survive the passage. PFN registers about 100 thousand meteors every year and for over 15 thousand of them we manage to determine precise trajectories and orbits. This project is developing all the time, engaging many ordinary people – not only scientists but also astronomy fans, individuals, special-interest groups and clubs, sometimes even entire schools.

The most interesting discovery of the PFN project is an identification of a resonant filament in the Taurid meteor complex which contains large bodies and might be potentially dangerous for our planet. As many as 10 large asteroids with orbits within this filament were identified. Among other achievements one can note the discovery of the Zeta Cassiopeids shower and the detection of the highest ever recorded Orionid meteor, which started to shine at height of almost 170 km.

The largest potential meteorite fall observed by the PFN is the Reszel meteorite associated with the PF120916 Piecki fireball which appeared on September 12, 2016 at

>> Fig. 3: The brightest fireball of the Perseids 2016 maximum captured by photographic station near Warsaw. Image credit: A. Olech.

21:44:07 UT over the Warmia and Mazury region and had a brightness of -9.2 mag. Very slow fireballs provide the highest chances for a dropping meteorite, and thus the delivery of valuable scientific matter to the Earth, and the Piecki event belonged to this category. It entered the atmosphere at an altitude of almost 82 km at a speed 17 km/s, and ended its visible trail at an altitude of 26 km, at a speed of only 5 km/s. Calculations have shown that up to 10-15 kilograms of cosmic matter reached the ground. The impact area was determined quite accurately. It is 4 kilometers long and 200 meters wide and is located less than 4 km south of Reszel city. Unfortunately, the most likely place of fall for fragments weighing about 5 kilograms was in Lake Kławój or in the surrounding wet and swampy terrain. Despite intensive search campaigns, the meteorite was not found.

Multi-station observations are a well-tried, proven method for registering brightness of meteors and their trajectories in the atmosphere, estimating mass and orbital parameters of meteoroids, and pinpointing places of meteorite falls. In the second half of the 20th century a clear leader in this area was the European Fireball Network which operated an extensive network of fully automated photographic stations. In the 21st century the meteor astronomy entered a new era thanks to the advent of modern techniques of digital image recording. When it comes to their practical usage, the Polish Comets and Meteors Workshop (Pracownia Komet i Meteorów, PKiM) is a pioneer. Starting from 2004, CAMK PAN and PKiM have been conducting a project named the Polish Fireball Network (PFN) in which CCTV cameras with fast lenses are used as main detectors. Currently, in Poland there are over 35 such stations with over 70 cameras.

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**Bartłomiej Zgirski, Piotr Wielgórski**

# New Polish astronomical observatory

Located in the Chilean Atacama Desert, the Observatory Cerro Armazones (OCA) is a facility placed in the area that provides one of the best possible conditions for ground-based observational astronomy in the world.

The observatory is located in the northern Chilean Coast Range which has a significant impact on the climate by providing a kind of wall for the humid ocean air and producing the *'rain shadow'*. On the other hand, the moist air from Amazonia is blocked by the Andes. Thanks to that, the surroundings of the observatory may be considered the driest non-polar desert on Earth with a great majority of cloudless nights during a year. Moreover, at the elevation of almost 3000 m the exceptional stability of the atmosphere and very low content of water vapor provide optimal conditions for optical and near infrared observations. For this reason the region has been chosen for several very famous astronomical projects. ESO's Cerro Paranal Observatory is located just 20 km away, the largest telescope in the world – the Extremely Large Telescope (ELT) – is being build at a stone's throw (at the summit of Cerro Armazones), while the Cherenkov Telescope Array (CTA) will be located on a nearby plateau.

The Observatory Cerro Armazones was established by the group of prof. Rolf Chini from the Astronomical Institute of the University of Bochum in Germany in collaboration with the Antofagasta's Catholic University of the North in 1995. The large distance between the observatory and the closest city (Antofagasta) made it impossible to supply the observatory with energy and water from the electric grid and water mains. Therefore it was designed to be 'self-sufficient'. Three photovoltaic arrays and windmills supported by a diesel generator provide electric power for the observatory. The observatory adopted its current setup in the early 2010s. Since then, there have been four telescopes operating at the hill: 0.8 m InfraRed Imaging Survey (IRIS) with an infrared camera cooled down

>> Fig. 1: The Cerro Armazones Observatory as seen from the top of Cerro Armazones.

with liquid nitrogen, the 0.4 m optical Bochum Monitoring Telescope (BMT), the 0.25 m Berlin Exoplanet Search Telescope II (BESTII), and the 2x0.15 m Robotic Bochum Twin Telescope (RoBoTT). Recently, the Leibniz Institute for Astrophysics Potsdam has built in OCA an 0.3 m telescope equipped with an exceptionally wide field camera allowing to capture about 200 square degrees in one image.

In 2016, a cooperation between Bochum and the Araucaria Project started. Our observers, present all year round at OCA, have been taking advantage of excellent atmospheric conditions and telescopes which are a perfect for the purpose of obtaining precise photometry of bright variable stars from our Galaxy. A dedicated observatory gives us an opportunity to collect multiwavelength light curves of hundreds of pulsating stars in the Solar neighbourhood which, together with their distances expected from the Gaia satellite mission, will allow for accurate calibration of primary distance indicators (Baade-Wesselink method, period-luminosity relations). It is also essential for observations of nearby eclipsing binary systems, which are crucial for improving the Polish cosmic ruler established by the Araucaria project.

In 2020, the observatory was donated to CAMK PAN and became the Polish National Observatory as a part of the European Southern Observatory. A generous grant awarded recently to prof. Pietrzyński by the Polish Ministry of Science and Higher Education enables modernization and enlargement of the observatory. First light of two new telescopes: 1.5 m and 0.8 m Ritchey-Chretien system (made by Astro Systeme Austria) equipped with new generation optical CCD cameras is expected in 2022. Moreover, a high resoultion spectrograph named Bochum Echelle Spectrograph for OCA (BESO) will be installed on the 1.5 m telescope in collaboration with the Innsbruck University. Such instrumentation combined with a non-limited observing time enables for a deep and precise study of the properties of different types of distance indicators in the Local Universe which is the crucial step for an accurate calibration of the cosmic distance scale and the determination of the Hubble Constant – the Holy Grail of astronomy and the main goal of the Araucaria Project. Therefore, the observatory is extremely important to support cosmic missions like TESS and Gaia, and big telescopes from nearby observatories in pursuit to measure our Universe, and as a result – to understand it much better.

The observatory provides excellent opportunities not just for strictly scientific projects. Maintenance of this independent observatory in superb environmental conditions is an excellent reason for the development, testing, and usage of various new instrumental and software tools that will secure progress in the field of observational astronomy.

Team members: Marek Górski, Mikołaj Kałuszyński, Paulina Karczmarek, Weronika Narloch, Dariusz Graczyk, Bogumil Pilecki, Monica Taormina, Wojtek Pych, Ksenia Suchomska, Gergely Hajdu, Grzegorz Pietrzyński (head), Piotr Wielgórski, Bartłomiej Zgirski

>> Fig. 2: The Araucaria team exploring the night sky in infrared with the IRIS telescope.
Image credit: M. Ramola.

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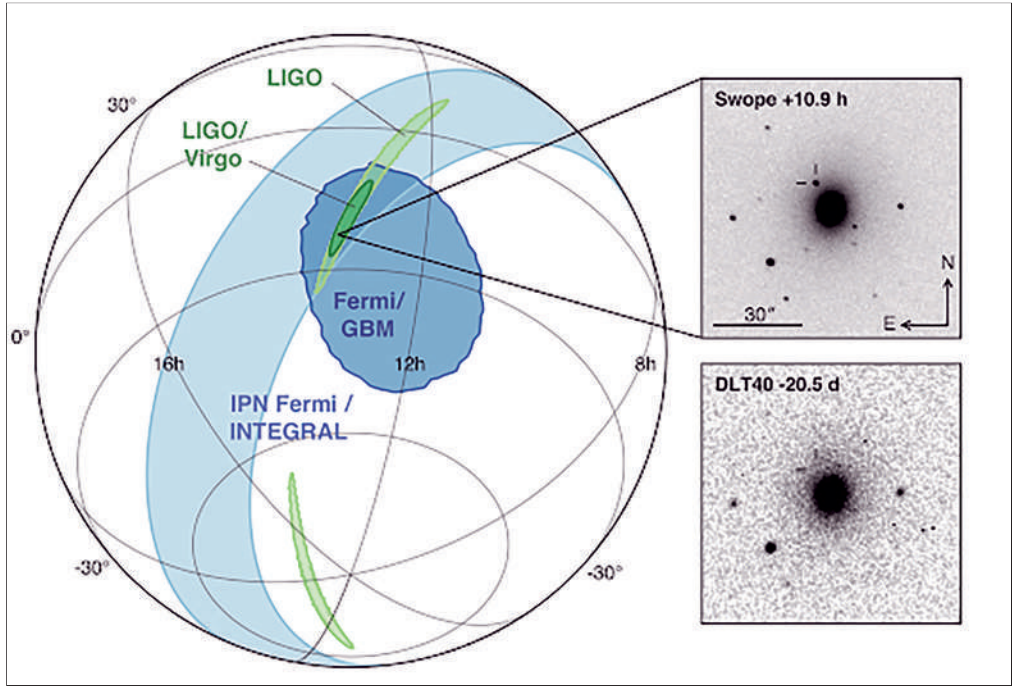
**Michał Bejger**

# Advanced Virgo, the European gravitational-wave observatory

Until recently, most of our knowledge about the Universe was derived from observations of electromagnetic waves (such as radio waves, visible light, X and gamma radiation). Gravitational waves - very small distortions of distances in space and flow of time caused by the movement of astrophysical objects, such as black holes and neutron stars - allow us to study areas that are not accessible to electromagnetic waves.

To detect these tiny fluctuations of space-time itself, extremely precise devices are required. One of them is the Advanced Virgo detector, a large-scale research infrastructure comprising a 3 km-long interferometric gravitational-wave detector built by the Centre National de la Recherche Scientifique (CNRS, France) and Istituto Nazionale di Fisica Nucleare (INFN, Italy). The detector is located in Cascina, near Pisa, Italy (see Fig. 1). Currently, the Virgo Collaboration consists of 28 research groups with almost 500 scientists from around 100 institutes from Italy, France, the Netherlands, Poland, Hungary, Spain, Germany and Belgium, participating in multi-messenger astrophysical observations of the Universe, as well as research and development of the detector.

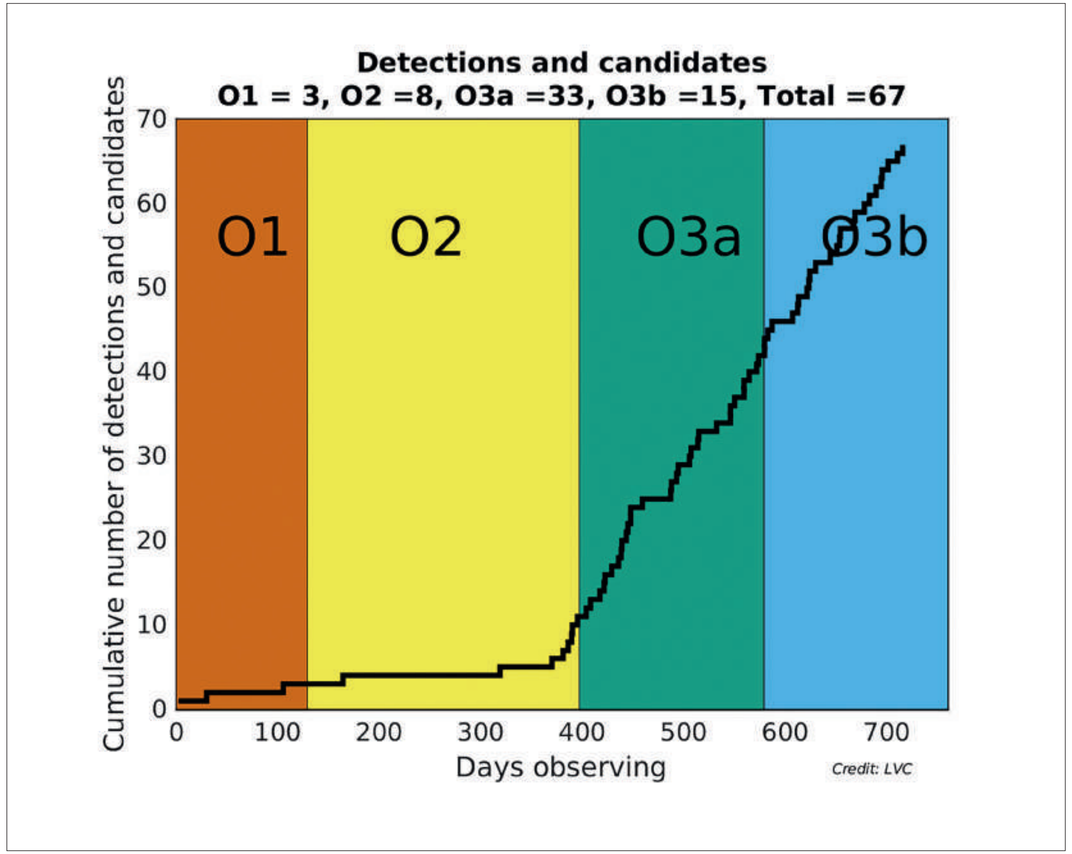
>> Fig. 1: Aerial view of the Advanced Virgo detector, located in Cascina, near Pisa (Tuscany, Italy).
Image credit: The Virgo Collaboration.



>> Fig. 2: Localization of the gravitational-wave, gamma-ray, and optical signals for the GW170817 event. The initial LIGO-Virgo triangulation (GW-only sky localisation of 31 square degrees and related distance measurement) provided enough information for the optical observers from the Swope and DLT40 projects to find the remnant of the merger: the kilonova signal in the NGC 4993 galaxy.
Image credit: The LIGO-Virgo Collaboration.

The Virgo group at CAMK PAN represents a substantial part of the Polish Consortium of the Virgo Project. Virgo forms a close collaboration with the US-based LIGO project, which has two 4 km-long gravitational-wave detectors, called Advanced LIGO. Researchers from CAMK PAN have therefore full and unrestricted access to the global LIGO-Virgo detector network worth about 1 billion US dollars, which means, among other things, unlimited access to the data collected by the 3 state-of-the-art gravitational-wave detectors. Due to the participation of CAMK PAN scientists in the LIGO-Virgo Collaboration (now LIGO-Virgo-KAGRA Collaboration, since the Japanese underground cryogenic detector recently joined the network), and their direct contributions to the recent discoveries of gravitational waves, CAMK PAN is currently in the forefront of one of the most exciting new fields of astrophysics (Fig. 2 shows the ability of global LIGO-Virgo detector network, able to triangulate source position using solely gravitational-wave data).

The discovery of gravitational waves has opened up completely new possibilities for astrophysical research, a new ''window'' to previously unseen objects and phenomena, uncovering their relation to the evolution of stars and the Universe. With the steadily-increasing sensitivity and currently practically routine detections of gravitational waves, CAMK PAN participates in conducting precise tests of Einstein's relativistic theory of gravity and alternative theories of gravity, studying the laws governing black holes and the densest matter in the Universe inside the neutron stars, as well as making independent measurements of cosmological parameters. Gravitational-wave astronomy only began to answer the most basic questions of physics and astronomy: how do black holes form, how abundant and how massive can they be? Is Einstein's theory the correct theory of gravity? How does matter behave when subjected to extreme temperatures and pressures in the interiors of neutron stars and during supernova explosions? What happened in the early Universe just after the Big Bang? With the increasing stream of new detections (see Fig. 3), these questions will be thoroughly addressed in the near future.



>> Fig. 3: Cumulative number of detections and detection candidates in the Advanced Era observing runs O1-O3. Advanced Virgo joined the network in the last month of O2.
Image credit: The LIGO-Virgo Collaboration.

In addition to questions that fascinate astrophysicists, the Virgo project is responsible for developing cutting-edge engineering and technology solutions, using the most advanced laser and optical technology, precision mechanics, electronics, and material physics. Despite reaching great sensitivity, detecting weaker sources of gravitational radiation requires further lowering the noise level in the detector. CAMK PAN makes a significant contribution here by studying the behavior of the detectors and by characterising the noise. It also contributes to identifying and reducing a certain type of noise resulting from changes in the gravitational field near the mirrors of the detector (so-called Newtonian noise; these technical aspects of the devices are carried out in the experimental division of CAMK PAN: the AstroCeNT). There are many examples of technology transfer from gravitational-wave interferometry to commercial applications in the industry. Using the challenge of detecting and characterising very weak gravitational waves buried in the noisy data as motivation, software solutions and methods for data analysis researched at CAMK PAN employ high-performance computing, machine learning and artificial intelligence methods, which have the potential to be applied in other fields of science and technology.

**Gerald Handler**

# The first Polish scientific space mission: studying the variability of the BRITEest stars

The BRIght Target Explorer (BRITE) Constellation is the first nanosatellite mission applied to astrophysical research, and the first Polish space mission. Five satellites in low-Earth orbits perform precise optical two-colour photometry of the brightest stars in the night sky. BRITE is naturally well suited for variability studies of hot stars. A brief summary of the first scientific results obtained by BRITE is given.

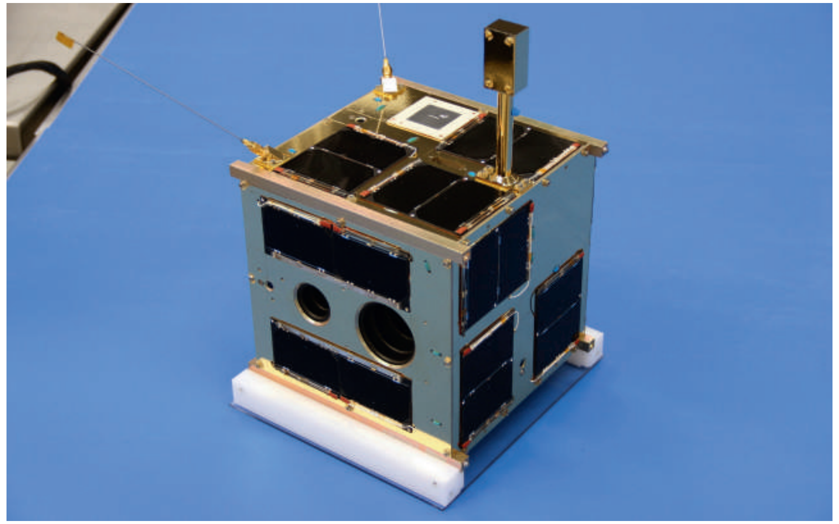
A BRIght Target Explorer (BRITE) is a nanosatellite designed as a cube of 20 x 20 x 20 cm edge length that weighs approximately 7 kg. It carries a 3-cm telescope with a 24-degree wide field of view on the sky that feeds an uncooled 4008 x 2672-pixel CCD. As such, it is predestined to obtain high-precision space photometry of apparently bright stars. Figure 1 shows one of the BRITE satellites in the clean room before launch.

There is more than one BRITE. Each of the partner countries participating in the mission, Austria, Canada and Poland, funded two satellites. One of each pair is equipped with a blue-sensitive, the other with a red-sensitive filter. The whole ensemble of satellites is called BRITE-Constellation and is therefore capable of multicolour time-resolved photometry.

The six satellites were launched into orbit between February 2013 and August 2014. One of the Canadian satellites, BRITE-Montreal, went astray during launch as it apparently did not separate from the last stage of the rocket. The remaining five satellites that operate are called BRITE-Austria and Uni-BRITE (both Austrian), BRITE-Toronto (Canadian), and the Polish satellites are named BRITE-Lem and BRITE-Heweliusz. The data acquired with the different satellites are transmitted to ground stations located in the respective partner country. The Polish ground station is located at CAMK PAN in Warsaw and operated by Grzegorz Wożniak and Grzegorz Marciniszyn.

At the time of writing, the Constellation has observed 628 unique stars (about half of them more than once) in 53 fields, and the data are being worked on by 38 international Principal Investigators. A typical BRITE run on a given field lasts for the whole visibility period if technically possible, i.e. about half a year. Some „legacy fields” are observed each year. The two-filter capability and long time baseline of the observations makes BRITE unique among photometric space missions.

One might naively think that all is known about the brightest stars and there is no point in aiming a space mission at them. Exactly the opposite is the case. Just because the BRITE targets are so bright, high-quality photometry of them proved to be difficult due to issues of lacking comparison stars and detector saturation. BRITE operates best in areas on the sky densely packed with stars - mostly the Galactic plane which has been avoided by many larger space photometry missions because the stellar images there are difficult to be resolved from each other - which is no problem when concentrating on the brightest stars.



>> Fig. 1: One of the mostly identical BRITE satellites in the cleanroom.
Image credit: UTIAS Space Flight Laboratory.

The science results of BRITE are too manifold to be described in detail here. Within the past four years 36 refereed journal publications and more than a hundred conference papers directly based on BRITE data have been published, and four science conferences with up to 200 international participants have been organized.

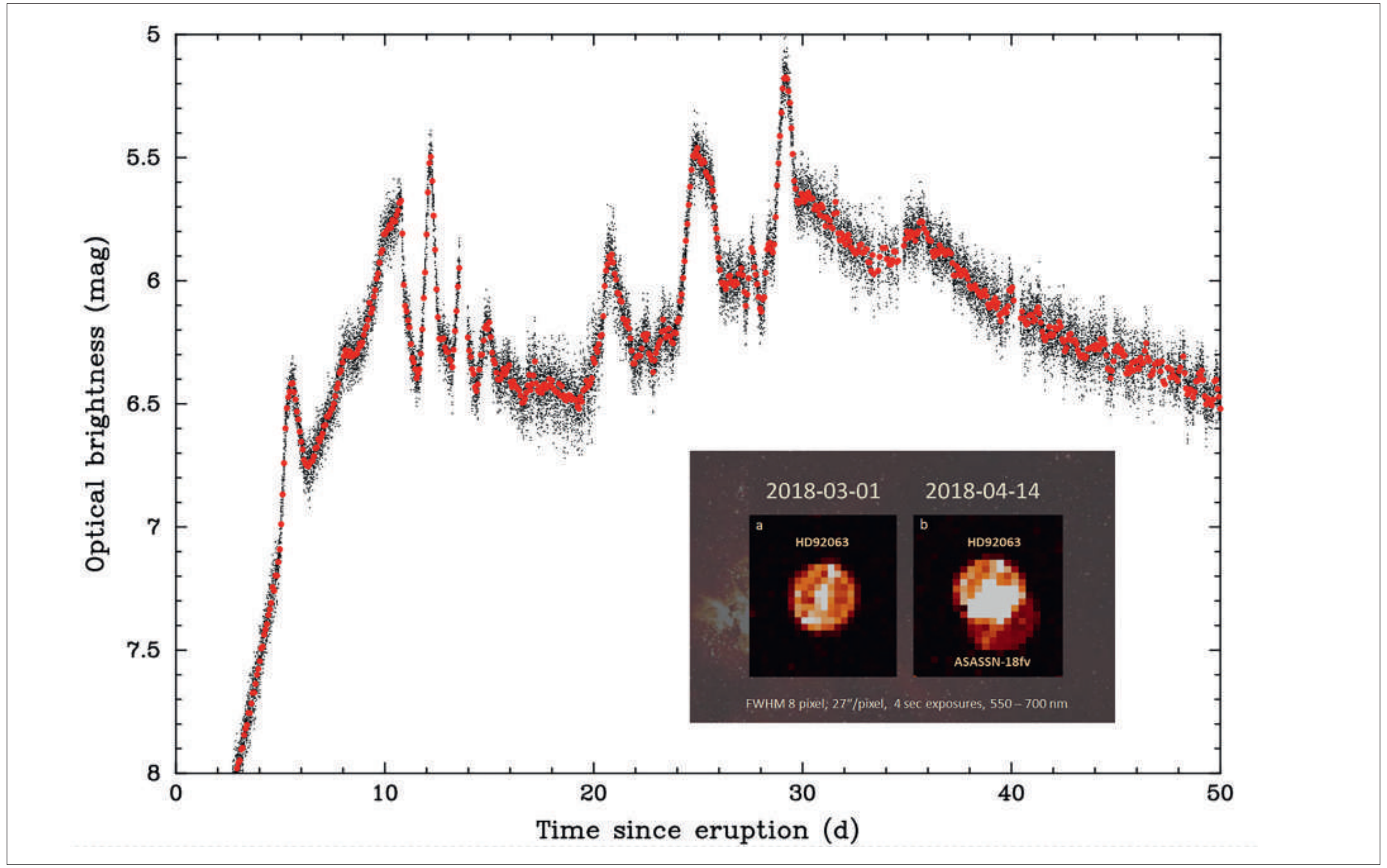
To sketch the impact of BRITE measurements on assorted areas of stellar astrophysics, we begin with massive stars. As expected from the high quality and long time base of observations, pulsating massive stars could be studied in deep detail because of the detection of previously unknown modes of oscillation. This allowed not only to better constrain stellar opacities, one of the most important ingredients for stellar structure calculations, but also resulted in measurements of differential interior rotation as well as detections of the influence of close binary companions on stellar rotation. The complex variability of rapidly rotating massive stars with emission lines in their spectra, the Be stars, was traced on the basis of several case studies to the presence of several internal interlocked „clocks” operating in those stars on time scales several orders of magnitude different. Stars with even more prominent emission lines, the Wolf-Rayet stars, were also studied with BRITE, revealing colliding winds in one close binary, fast apsidal motion in another, and chaotic wind variations in one apparently single star.

Moving to stars of solar mass or somewhat higher, the rapid pulsations and rotational variations of magnetic chemically peculiar star were studied with BRITE, and differential interior rotation of a more slowly pulsating star was detected. BRITE data also proved to be useful to extend the study of solar-like oscillations to the brightest red giant stars. A search for planetary transits and oscillations of a bright planet hosting star was sucessfully carried out.

Of course, having data of unprecedented quality and quantity in hand, some real breakthrough results and unexpected discoveries can be made. BRITE is no exception in that respect. For over a quarter of a century, the question of whether and how the source of the variations of the winds of massive stars is rooted to the stellar surface was open and has prompted extensive theoretical work. BRITE observations combined with spectroscopy gave the answer: it is magnetic fields that lock the stellar wind variations with surface rotation.

Regarding discoveries, BRITE detected the first two examples of massive so-called „heartbeat stars”, close binaries in eccentric orbits where the gravitational pull of the companion periodically distorts the shape of the primary star and can even give rise to forced stellar oscillations. Interestingly, one of these binaries consists of two magnetic stars. Another object in which BRITE may have detected forced oscillations is the nearby supernova candidate Eta Carinae. The most unexpected BRITE discovery was however the sudden appearance of a „new star" on the images taken with one of the satellites. It turned out that a Nova outburst had happened in the immediate vicinity of one of the stars observed, and therefore BRITE was able to provide the most precise and most densely covered Nova light curve, from outburst until several months after, ever recorded. This light curve provided direct evidence for shock-powered optical emission in a nova and is shown in Fig. 2.

Originally designed for a lifetime of two years, the BRITE satellites have now been in space for over six years. They have more than fulfilled the expectations set for this mission. Some satellites, in particular the Polish Heweliusz, are still in very good shape and are expected to operate for several more years to come.



>> Fig. 2: Light curve of the Nova V906 Car as registered by BRITE. Black dots are individual measurements, red points orbital averages. The inset shows an image of the originally observed star HD 92063. Left: before the eruption, right: during eruption.
Image credit: Rainer Kuschnig.

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**Agata Różańska**

# ATHENA – Advanced Telescope for High ENergy Astrophysics

ATHENA is the second "Large-class mission" selected by ESA as part of Cosmic Vision plan, with the launch foreseen in 2032. ATHENA is a new generation X-ray telescope for the detection of photons of energies between 0.2-12 keV. The state of the art X-ray mirrors used in ATHENA will allow to achieve an effective area of 1,4 $m^2$ at 1 keV, which is ten times more than in any currently working X-ray mission.

ATHENA will have two focal plane detectors: X-IFU (X-ray Integral Field Unit) and WFI (Wide Field Imager). The first detector will be an array of micro-calorimeter sensors. Each sensor will measure small changes of the temperature caused by incoming X-ray photon. The whole sensor has to be kept in a very low temperature (50 mK) Dewar type cylinder. This design is crucial to achieve an extremely good spectral resolution of 2.5 eV at 1 keV, which is needed to observe numerous narrow lines from highly ionized heavy elements from different sources.

The second detector will be an array of Si-based active pixel sensors (ASP) with fast readout of the order of few micro-seconds. WFI will make it possible to observe bright variable objects such as pulsars and X-ray binaries with black holes or neutron stars. Thanks to ATHENA's high sensitivity, we will detect objects with redshifts up to 3. In addition this detector is going to have large field of view, which is crucial to study the distribution of hot gas in galaxy clusters.

The main science goal of the ATHENA mission are the following:

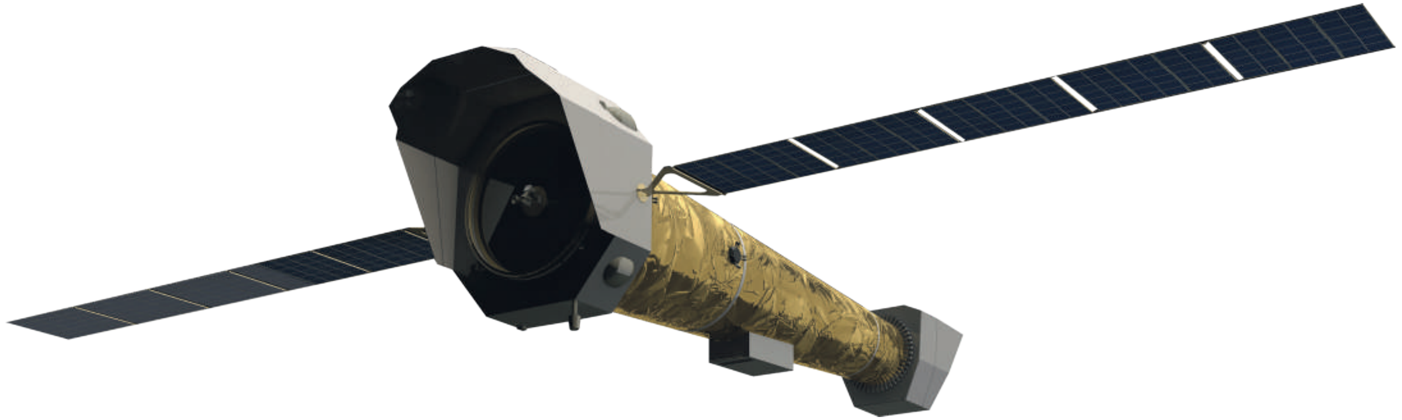
- interaction of galaxy clusters with intergalactic gas including: processes driving the evolution of chemical enrichment in the hot diffuse gas in large scale structures, how and when did the first galaxy groups form?
- warm hot intergalactic medium (WHIM): where are the missing baryons in the local Universe, what is the underlying mechanism determining the distribution of the hot phase of the cosmic web,
- feedback in clusters of galaxies: how do AGN (active galactic nuclei) jets and winds dissipate mechanical energy in the hot intracluster medium, and how does this process regulate gas cooling in those objects,
- AGN feedback (including our Milky Way), direct monitoring of hot, ionized outflows: how do accretion disks around black holes launch winds and how much energy do these carry, how are the energy and metals transferred into the intergalactic medium,
- close environment of supermassive black holes (SMBH): what is the relationship between the accretion disk and the surrounding hot plasma, and what is the black hole spin,
- ATHENA will also observe many closer objects such as: the solar system and exoplanets, the end points of stellar evolution and supernova remnants.

Polish scientists and engineers participate in the design and construction of the both detectors (for details see: https://athena.camk.edu.pl). Scientifically we provide input in ATHENA working groups. The goal is to define instrument requirements which will allow to make the best observations. We work in the following topics: evolution and formation of SMBH, physics of accretion, close environments of SMBH, AGN wind and star formation regions, warm absorbers, warm hot intergalactic medium and neutron star atmospheres. Our models are used to simulate signals for satellite detectors.

Polish engineers from CBK PAN and the Astronika company are responsible for the design and implementation of four components:

1. Filter Wheel Assembly (FWA), for WFI detector. This is a system for changing the optical blocking filters and its special position allows for instrument calibration,
2. Power Distribution Unit (PDU) for WFI. A system for power distribution between individual instrument modules. The total power to be distributed is around 750W.
3. Power Distribution Unit for X-IFU detector with total distributed power 3kW. The system is functionally similar to the WFI, but works in a different range of distributed power, with a different number of receivers and other implementation requirements.
4. Dewar Door (DD) for X-IFU detector. The main aim of the Door designed by Astronika for the ATHENA mission is to maintain a vacuum inside the Dewar containing the X-IFU instrument. The Door will also need to enable measurements to be taken, meaning it will need to allow for X-rays of a designated energy spectrum to pass through. Finally, the Door will also need to allow for a direct calibration of the sensors situated inside the Dewar without the necessity of unsealing the whole system. It is important to note that due to volume constraints, the Door will need to open in a plane parallel to the surface of the sealed opening. Fulfilling these requirements requires the development of a novel solution, which can also be used in other subsequent space missions.

Team members: Agata Różańska (member of WFI Science Team, and member of X-IFU Consortium Board), Grzegorz Woźniak, Monika Zuchniak, and Piotr Życki (member of WFI Consortium Board) – all from CAMK PAN, and a group of scientists from twelve institutes around Poland. We vigorously collaborate with engineers from CBK PAN and the Astronika company. All Polish contributions are paid by the ESA PRODEX program which allows to use national money to build scientific space missions.



>> Fig. 1: Artistic vision of the ATHENA telescope in orbit. Image credit: X-IFU Consortium.

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ISBN 978-83-64273-49-0