4.1.1 Executive summary

The objective of STRONGGRAVITY was to develop analytical tools to study processes occurring near astrophysical black holes, to acquire observational data on the Galactic solar-mass black holes in binary systems, super-massive black holes in the centres of galaxies and our central black hole of the Milky Way, and to use the created tools together with the new and archival data for better understanding the properties of black holes and their immediate neighbourhood.

Black holes provide a crucial link between Einstein's theory of gravity and real cosmic objects which astronomers can observe and study in the Universe. This project was oriented towards the legacy of the cornerstone XMM-Newton X-ray satellite mission of European Space Agency in synergy with relevant data in other spectral domains covered by ground-based infrared and radio interferometric techniques at European Southern Observatory and elsewhere. Information in different wavelengths was gathered and explored in order to understand radiation processes in places of strong gravity, near black holes.

Over the course of the project, we have developed a collection of sophisticated numerical tools and physical models that help to better understand the processes and the physical nature of the environment around black-hole sources. These tools are either completely new or have been greatly enhanced compared to the initial state. We have also sought valuable data from archives and complemented them by performing new observations where needed. Those data has been analysed by our computational tools and the results of such analyses were published in highly impacted peer-reviewed astronomical journals. Over the course of the project there have been over 170 such papers. We have issued two ESO press releases and one ESA press release on some of the extraordinary achievements with wide impact to the astronomical community and to general public.

4.1.2 Project objectives

A. Theoretical methods and analytical tools

One of our main tasks in this project was to develop new methods and analytical tools that would be used later in the project or by wide astronomical community after the project was finished, with the observational data to model the physical properties of the observed systems, AGN, Milky Way central black hole or galactic black holes in binaries. Thus one of the main objectives was to create codes and tables, that could be employed inside widely used analysis packages like, e.g., XSPEC for the X-ray spectral analysis. All of the tools were tested thoroughly and used with real observational data. These tools were developed in the following topics sorted in framework of work packages.

a) Primary X-ray emission

The main objective was to develop a Monte-Carlo simulation tool to calculate the spectrum and polarization of Comptonized radiation, i.e. emission due to the thermal seed photons from the accretion disc that are Comptonised in the corona above the disc. Both the special relativistic (SR) and all general relativistic (GR) effects were included. This was needed so that the code is capable to model the emission in AGN and GBH systems. The development of this new scientific tool was the goal of WP4.

b) Modelling the reprocessing by standard accretion discs in AGN

Spectral modelling

We planned to develop a more advanced reflection model in lamp-post geometry that apart from the iron line would also include the continuum part of the reflection, and that would apply the correct fraction of the reflected flux given the height of the primary source. To this purpose new table models would be produced for the local disc emission that take into account a broad range of possible ionisation states and accurately treat the emission directionality. The ionization may change with the disc radius according to its temperature and/or irradiating flux. This was the task for WP2.

Time Lags

Our aim was to develop a reverberation mapping code for computing the X-ray light curves of both the primary X-ray and the reflection components and for computing theoretical lags versus frequency and energy dependences. Newly created tool should be available as an XSPEC model so that the code may be easily used for fitting the real X-ray reverberation data. This work constituted WP6.

c) Reflection from standard and slim accretion discs in GBH systems

Spectral reprocessing and the vertical structure of accretion discs

In this topic we planned to focus on getting slim disc solutions with self-irradiation. Before the project started, there already was an existing numerical scheme that was capable of solving disc structure equations with a given irradiation field. This scheme had to be repeated few times with an updated radiation field at each step until a converged disc solution was found. With a disc structure in hands we aimed to calculate the shape of local emergent spectra using our radiative transfer code.

Then we planned to focus on improving on the detailedness of the underlying physical models of thermal emission of stellar-mass black-hole accretion disks and to improve on accuracy of the modelling with respect to the observational evidence. This work was the task of WP10.

Coupling the coronal emission to the reprocessing of standard discs

In this topic we planned to investigate the radiative coupling between the corona and a standard geometrically thin and optically thick accretion disc. While in WP10 we were to focus on the disc properties (such as viscosity or accretion rate), here we were mainly to consider the properties of the corona. To achieve this goal, we planned to apply several codes: TITAN, to obtain the ionization and temperature structure of the disc, the Monte-Carlo code STOKES, to compute the spectral and polarization properties of disc emission, and MoCA code, developed in WP4, to compute the resulting primary X-ray spectrum emerging from the corona. The correct primary and reprocessing spectra were to be obtained after iteration between the Comptonization code MoCA and STOKES/TITAN. Close to the black hole we additionally wanted to apply the GR ray-tracing methods developed at AsU to take into account the GR effects. This task was to be carried out in WP11.

d) Variability in GBH systems

For the low-frequency quasi-periodic oscilations (QPO) the most advanced model is the Lense-Thirring precession model. The current formulation of the model enables simulating the energy dependencies of the QPO amplitude, and it can be extended to predict also the advanced timing characteristics. The high frequency QPO in black hole systems are certainly even more relativistic phenomenon than the low frequency QPOs. The resonance model of Abramowicz & Kluzniak makes predictions for the energy dependencies. We planed to extend the model to compute other spectral/timing characteristics to compare them with the data and to develop a Monte Carlo type code to simulate energy spectra from precessing/oscillating hot flows, with uniform plasma temperature including all relativistic effects. Our aim was also to perform simulations to create a grid of models to compute observable characteristics: power spectra, amplitude of variations and time lags. This task was carried out in WP13.

e) Winds and the warm absorber in AGN and Galactic sources

We planned to use TITAN photoionization code to model the accretion disc winds and warm absorbers with the aim to determine their physical properties i.e. column density, inclination, distance. We planned to consider absorber under a constant total pressure, which allows to use one single absorber instead of several constant density zones used by many observers. We plannned to construct grid of models for particular sources. The most interesting one was Mkr 509, since multi-wavelenght observational campaign of this source is almost completed. As a result broad band spectral energy distribution of radiation, which may affect the wind, was determined and we could use this to calculate models precisely for this source. The results were to be implemented as table models to XPEC fitting package. The model should mostly apply to AGN. The modelling of disc winds constituted WP5.

f) Multi-waveband modelling of Sgr A*

We planned to modify an existing numerical code to model radiative processes assuming various geometries for flaring events. The final code should be capable of calculations of polarized light curves in the strong-gravity relativistic regime, it should handle arbitrary geometrical set-ups and non-stationary configurations, and it should trace photons from optically thick surfaces or through optically thin media while accounting for emission/absorption at each place including polarization characteristics of the escaping radiation. With this new tool we planned to simulate processes that can lead to NIR/X-ray flares and model observations of Sgr A* taken simultaneously in different frequencies and NIR polarization light curves in order to learn about the mechanisms and the geometry of the emitting source and to constrain the spin of the black hole, its inclination and projected orientation on the sky. We planned to use the developed code to create the library of simulated light-curves, which would include variability of polarization patterns for different source geometries. We were to focus on the hot-spot model (e.g., bright overdensity on the middle plane of the accretion flow), and allow for variations (within reasonable ranges) of the system's inclination with respect to the line of sight, the spot size, and its radial position with respect to the central black hole. The user would be also able to choose between an optically thin or thick accretion disk, and the orientation of the magnetic field: azimuthal or vertical. These tasks were included in WP8.

B. Scientific exploitation of data

Following the development of the tools we planned to apply them as they were ready to the observational data. We would conduct extensive work on the scientific archives of XMM-Newton at ESAC and, for our research on the Galactic Centre, also include infra-red data obtained at the European Southern Observatory (ESO). Aside from the data of the ongoing ESA mission XMM-Newton, we would also aquire and use the data of the approved new X-ray satellite NuSTAR. Based on our archival and modelling work, we were going to put in new observational proposals for XMM-Newton and other space- and ground-based observatories being available during the project period. We further intended to use the new tools developed by our consortium in the preparation of the ESA mission projects or for European contributions to NASA missions, and thus help to most accurately estimate the scientific performance of ESA's and NASA's next-generation X-ray observatories.

a) Active Galactic Nuclei

Iron Line Profiles

We expected new results from new X-ray facilities – in spring 2012 NuSTAR (a NASA mission with small European contributions) was launched, the first X-ray satellite with focusing imaging in hard X-rays (up to 80 keV), allowing for an increase of two orders of magnitude in sensitivity above 10 keV. The very broad band available when combining XMM and NuSTAR would permit to definitely confirm the relativistic line model, as this model and the complex absorption model make very different predictions in hard X-rays. Moreover, once the relativistic model would be validated, the broad band would permit an unprecedented control of the spectral continuum, and therefore a much more precise and robust measurement of the spin of the black hole. These studies, which would make use of results from WP2, WP4 and WP5, were the main aim of WP3.

Time lags

We planned to make extensive use of the XMM-Newton archive to search for X-ray light curves with high enough quality to be used for soft lags detection. Moreover, we were to propose new observations of objects with known black hole mass in an attempt to perform soft lags searches over the widest black hole mass and luminosity/Eddington ratio ranges. Simultaneous XMM-NuSTAR observations would permit to extend the search for time lags to the hard X-ray band. These studies, based on results from WP6, were the aim of WP7.

b) SgrA*

Special emphasis should be put on tracing the variability of Sgr A* in the radio to sub-mm bands and investigating how it is linked to the NIR and X-ray variability. Immediate goal was the exploitation of the 2012 observing campaign as well as the data that we obtained in the project period through interferometry in the NIR at the Large Binocular Telescope (LBT, a joint USA/Europe facility) and at the ESO's Very Large Telescope Interferometer (VLTI).

It is important to consider relativistic effects on the polarized light produced in such strong gravitational environment in order to describe the observations more accurately. In the NIR domain a detailed investigation of the polarization information was essential. Here we were probing the optically thin part of the innermost accretion flow and have the possibility to trace the effects of strong gravity. In the past years, we had performed simulations using the KY-code (developed in collaboration between AsU and UCO) being able to model parts the polarized variable-emission of Sgr A*. We planned to use it in conjunction with the new 3-dimensional code to constrain the geometrical properties of the source from the data. Relativistic modelling of polarized flares and sub-mm/X-ray light curves was essential to support (or even proof) the existence of orbiting matter in a mid-plane of the accretion flow onto Sgr A*. These studies are the aim of WP9.

c) Galactic Black Holes

Spectral modelling

We planned to search the data archive of XMM-Newton for the X-ray spectra of galactic black holes with dominant thermal component and search the spectra for possible reflection features. Using the spectral models for the thermal emission (WP10) and the ionized reflection (WP2) developed by us, we planned to measure the spin of the galactic black holes in these sources with both the iron line profile and the thermal continuum models, permitting to test and validate both models.

In this observational work package we also wanted to use the QPO tool (WP13), we were going to develop, to compare predictions with data and try to understand which of the current scenarios fit to the observational constraints.

Additionally we planned to apply the slim disc model (WP10) to archival XMM-Newton data of ULX sources.

4.1.3 Results of the project

During the whole duration of our project the research work progressed according to our planned objectives with some deviations that are to be expected in such a large scientific programme. Our research was, on one hand, concentrated in creating analytical tools and models that are now available freely for the astronomical community to be used with the observational data, and on the other hand, we acquired new observational data in successful proposals that we used for our own research in this project. These data are also available freely for the community to do other types of studies not covered in our project.

We also joined efforts with the world-wide astrophysical research community in proposing new observational missions planned in either European or US schemes for mission funding through ESA (small, medium – M3 and M4, and large – L2 missions) and NASA (Small explorer missions – SMEX). We contributed to the following mission proposals by helping with coordination of work, with writing the scientific justifications of missions, white and supporting papers as well as with the estimation of their scientific performances by simulations:

Mission proposals finally not approved:

- **LOFT** – *The Large Observatory for X-ray Timing* submitted for the M3 and M4 ESA calls for medium missions,
- **XIPE** – *The X-ray Imaging Polarimetry Explorer* submitted for the first ESA call for a small mission and in the upgraded version for the M4 ESA call for a medium mission, where it was selected with two other missions for the further study, with a final decision in 2017 in favour of the one of the other two competing missions,
- **PolSTAR** – the X-ray polarimetry mission submitted for the NASA SMEX in 2014,
- **XILPE** – *X-Ray Imaging Light Polarimetry Explorer* being prepared for the second ESA call for a small mission in collaboration with Chinese CAS.

Approved missions:

- **ATHENA** – *Advanced Telescope for High-ENergy Astrophysics* accepted for funding in the L2 ESA call for a large mission with a launch in 2028,
- **IXPE** – *The Imaging X-Ray Polarimeter Explorer* submitted for the NASA SMEX in 2014, and accepted for funding with a launch in 2021.

Acceptance of the *Athena* proposal by ESA was a major success for the astronomical community since it will be the largest X-ray astronomical observatory ever built. It will enable transformational advances in many topics of X-ray astronomy that are summarised in the Athena white paper *The Hot and Energetic Universe*. Many researchers from our consortium contributed to the scientific study of the *Athena* (see the author lists of the White paper and Supporting papers for the mission available at http://www.the-athena-x-ray-observatory.eu/resources/publication-list.html).

Moreover, Andy Fabian is a member of the Athena Science Study Team (http://www.cosmos.esa.int/web/athena/team-membership) and Giorgio Matt, Giovanni Miniutti with Michal Dovčiak are coordinators of the Athena Science Working Group "The close environments of supermassive black holes".

Our team contributed heavily to the X-ray polarimetry proposals, mainly to their scientific cases. Several members of the consortium actively took part in the yellow book preparations for the European *XIPE* mission. Moreover, René Goosmann and Giorgio Matt were working group chairs for "Scattering in aspherical geometries and accretion Physics" and "Fundamental Physics", respectively, and Frédéric Marin and Jiří Svoboda were subworking group chairs for "Molecular Clouds & Sgr A*" and "Strong Gravity", respectively.

While the *XIPE* mission proposal was finaly not accepted, the NASA's SMEX mission *IXPE* was and thus, at last, in 2021 the new window in X-ray astrophysics will be opened. We are proud that members of our team were indispensable in the scientific proposal preparations and we continue to be a vital part of the follow-up mission preparations, where Giorgio Matt is a co-I of the mission and a chair of the Science Advisory Team, Michal Dovčiak is a chair of the "Accreting Black Hole" topical working group and Fréderic Marin is a chair of the "Radio-quiet AGN and Sgr A*" topical working group.

In the other wavebands, the group of Andreas Eckart (UCO) contributed to the Mid-Infrared Instrument (MIRI) on James Webb Space Telescope (JWST) and the Mid-infrared E-ELT Imager and Spectrograph (METIS) on the European Extremely Large Telescope (E-ELT).

Our efforts in helping with mission proposals and preparations were in accordance with our intention to use the analytical tools provided by our project in the preparation of the ESA mission projects and to provide accurate simulations for the scientific performance of next generation space-based X-ray observatories.

In the following sections, a detailed description of achievements during the project are described according to the division of our research into different work packages.

WP 2: Reflection from black-hole accretion discs – tools

The main aim in this work package was to develop a self-consistent reflection model for AGN in the lamp-post geometry as part of the KY package created previously at AsU. We have prepared several models – KYNLPCR, KYNREFIONX and KYNXILLVER. These models implement the geometry where the primary source of X-ray emission is approximated by a point source on the rotational axis of the black-hole-accretion-disc system which determine the illumination pattern on the disc. The models differ in the assumptions on the local disc emissivity, where KYNLPCR uses the tables computed by us (see below) for neutral accretion disc, KYNREFIONX use the REFLIONX tables for ionised disc available in XSPEC (created by UCAM in the past) and KYNXILLVER uses the most recent tables (García et al. 2013) also for ionised accretion disc.

During the first period we have also realised that the latest versions of XSPEC introduced different way of Fortran77 models compilation which broke the KY codes inside XSPEC that use more computational threads. The threads were used in non-axisymmetric versions of KYN to speed up the computations when more CPU cores are available. After some discussion with the XSPEC team we decided to translate the KY from Fortran77 to C programming language so that we avoid this and other possible compilation problems in the future. We managed to translate and test all non-axisymmetric KYN models.

Further, on suggestion from CSIC, we have implemented obscuration into the non-axisymmetric KYN models as a new feature. Up to now it was only possible to use emission defined either as a full disc emission, emission from a ring or emission from an azimuthally and radially defined segment of the disc (simulating a hot spot on the disc). The new feature allows to define an obscuration by a circular cloud defined in the observer's sky.

Another goal within this work package was to compute a comprehensive grid of synthetic reflection spectra emerging from an irradiated accretion disc. The specific requirement for the new model was to take into account in great detail the angular dependencies of the incident radiation and the reprocessed emission. In this work package we have obtained complete computations for a 2-200 keV reflection grid of a neutral disc, REFLSPECTRA.FITS. This new table model that takes into account all angular effects on the re-emission spectrum has been implemented in a relativistic model KYNLPCR.

WP 3: Black-hole spin measurements via reflection – AGN

The main aim of this work package was to exploit the X-ray data archives and propose new observations with available X-ray satellites with a goal to study the physical properties of corona and its location, the resulting disc ionization and properties of the warm absorber with the ultimate goal to make the measurements of the spin of the black holes as precise as possible.

Initially we mainly focused in the exploitation of the X-ray data archives to measure the BH spin in AGN with the tools available at the beginning of the project. We therefore completed the analysis of the X-ray data of many bright AGN, leading to well-constrained estimates of their BH spin, thanks to the unprecedented quality of the broad-band simultaneous spectra taken by NuSTAR and other lower energy missions, in particular XMM-Newton.

Later in the project we applied the theoretical models developed in other work packages (WP2 and WP4 for computing the X-ray emission in AGN and WP5 to characterize the warm absorption) to X-ray data with the ultimate goal to improve the measurements of the spin of the BHs, making them as precise as possible. This task brought the theorists and observers together – the data analysis part of the research benefited from the numerical codes developed within the project, while the code developers received valuable feed-back directly from the observers to further improve their tools.

Highlights

- The analysis of the NuSTAR data of bright AGN led to the publication of many papers on international refereed journals, authored and/or co-authored by participants of our project.
- A fully characterised catalogue of AGN with multiple X-ray observations in different epochs was created, with all the data collected from the archives and reduced to high-level spectra ready to be analysed.
- A full comparison between the spectra computed by MoCA code (developed in WP4) and a phenomenological cut-off power-law was performed.
- An XSPEC model out of the Comptonized spectra computed by MoCA was created, allowing for direct fitting of the data with the MoCA self-consistent model. The Xspec model was used in a sample of AGN observed by NuSTAR, as well as single very bright sources.
- A systematic comparison between the BH estimates derived with KYREFLIONX (developed in WP2) with those derived with similar public relativistic models in a sample of bright AGN has been performed. The effects of warm absorption (computed in WP5) were fully taken into account. We noticed that different codes often lead to the same BH spin estimate for the same source, but with notable exceptions. These results were published in a Master's Degree Thesis.
- Several our proposals for new observations of bright AGN, in particular with NuSTAR, were accepted, increasing considerably the available data for BH spin estimates in AGN for the whole community.

WP 4: Comptonization models: spectra and polarization

The objective of this working package was to develop a new, fully relativistic Monte Carlo code to compute the spectrum and polarization of the continuum emitted in a corona of hot electrons via inverse Compton on UV/Soft X-ray photons emitted from the accretion disc. The reason for developing such a code was twofold: on one hand, to have a code able to calculate Comptonization spectra also in regimes (i.e. large optical depths) where analytical models are no longer valid; the advent of the NASA satellite NuSTAR, providing for the first time grazing incidence imaging up to ~80 keV made this task particularly important. On the other hand, to have a code able to calculate the polarization of the scattered radiation with a full relativistic approach, and using the Klein-Nishina cross-section (most codes adopt the Thomson approximation, inadequate for very hot electrons). At the time of the proposal, the X-ray polarimetric NASA mission GEMS was expected to be launched shortly. The mission was eventually cancelled, but other missions were proposed afterwards, with one of them (IXPE) now approved by NASA for a launch in 2021.

The task was divided into two steps, first the fully special relativistic code without GR was developed which was then coupled with a general relativistic ray-tracing routine. The final fully general-relativistic code, named MoCA (MonteCarlo code for Comptonization in Astrophysics) was completed, fully tested and is available for the community.

Highlights

- The non-GR code is described in Francesco Tamborra Ph.D. thesis.
- The code was used to fit the observational data and get constraints on physical parameters of the accretion disc corona in AGN in the work package WP3.
- The code was extensively used during the preparation of the scientific case for the "Yellow Book" of the ESA M4 mission XIPE (X-ray Imaging Polarimetry Explorer), and we expect that the code will be also used during the preparation of the observing plan for, and in the interpretation of the results from, the Imaging X-ray Polarimetry Explorer (IXPE), a NASA/ASI mission to be launched in early 2021.

WP 5: The influence of the warm absorber on relativistic line profile

In this work package we studied outflowing winds in active galactic nuclei to examine their influence on the final iron line profile emitting in the vicinity of a black hole. Those outflows are visible in X-ray domain, and therefore called warm absorbers. Radiation which originates in the inner part of the disk due to reflection or accretion has to pass through the warm absorber. This process causes many narrow absorption lines in the transmitting spectrum, which is observed by us.

For better understanding the observational interpretation of winds we made an X-ray data reduction of SUZAKU data in case of X-ray binaries, showing similar behaviour.

We started our research on physical properties of absorbing material by testing thermal instability caused by strong irradiation in case of our Galactic Centre (GC). We showed that the radiation from Sgr A* past activity was strong enough to produce clumps at the distance up to 1.4 pc from GC. The location of those clumps agrees with the position of mini-spiral regions observed in our Galaxy.

In parallel, we constructed table models of warm absorbers using photoionization calculations of gas under constant total pressure (gas plus radiation). For this purpose we also constructed initial spectral energy distributions (SED) for different AGN depending on mass accretion rate and black hole spin and taking into account hard X-ray component parametrized as a power-law. In addition, input parameters devoted to the physical conditions of absorbing gas such as ionization parameter, surface volume density and total column density had to be specified. We performed computations for more than forty different SEDs and we found out that adding iron line profile to the SED before it reaches the cloud is equivalent to the convolution of our transmitted spectra with emission, i.e. emission line profile. Iron line profile does not change significantly overall spectral distribution and the dependence on spin is negligible. We found that such line does not change ionization structure since its profile has very small amplitude in comparison with the total spectrum.

Further we studied the properties of ionized gas in AGN by modelling the absorption measure distribution observed in 8 objects. Only one source showed different behaviour – Mrk 509, where AMD displays two dips. All other sources showed only one dip located at lower ionization parameter. We considered AMD for the case of Mrk 509 and using multi-wavelength observations as the intrinsic SED we computed many photoionization models assuming that absorber is under constant total pressure. We used TITAN (Dumont et al. 2000) photoionization code which computes radiative transfer through the matter with heavy elements in two stream approximation and lambda iteration method. We managed to reconstruct absorption measure distribution (AMD) for the Mrk 509 from photoionization modelling. Our modelled AMD for this source agreed with the observed AMD presented by Detmers et al. 2011 using XMM-Newton observations.

Based on the large grid of computed models we made systematic studies of absorption measure distribution (AMD) of ionized gas for different SEDs and gas density at the illuminated phase of cloud. In the first step we found that the modelled AMD can reproduce observations of Mrk 509 only if cloud density is high of the order of 10^{8} cm^{-3}. This idea was also incorporated in our research of Intermediate Line Region (ILR), where we demonstrated that only high density clouds can emit lines of intermediate width recently observed in AGN.

Absorption measure distribution in AGN is very broad spanning three orders of magnitude in ionization parameter. From systematic studies of AMD as clouds under constant pressure illuminated by different SEDs we found that the AMD normalization depends on the strength of the optical/UV bump and relative optical to X-ray luminosity. When the spectral energy distributions is dominated by strong big blue bump and weak X-ray power-law, the normalization of AMD is two orders of magnitude lower than in opposite extreme case of weak big blue bump and strong X-ray power-law. This conclusion puts constrains on the nature of illuminated continua of 7 observed AMDs which display the same low normalization of the order of 10^{21} cm^{-2}. Nevertheless, the position of dip caused by thermal instability of those 7 AMDs is still under discussion. We found that the only explanation is again high density gas. Only for cloud density of the order of 10^{12} cm^{-3}, we found the position of AMD dip in agreement with observations.

WP 6: Soft X-ray lags in AGN: theoretical modeling

The goal of WP6 was to develop theoretical models suited to model and interpret the observed X-ray time delays (lags) in accreting supermassive black holes.

The main aim was to produce a numerical code capable of producing lag-frequency spectra between two selected energy bands and a code that should include a reliable description of the spectral shape of the delayed component (neutral/ionized reflection off the inner accretion flow) in order to provide lag-energy spectra for any selected frequency band. Both numerical codes needed to consider all relativistic effects arising in the strong field regime of General Relativity, in the immediate vicinity of the accreting black hole.

We have build a numerical model of the time-delays between the primary X-ray emission from a point-like source positioned on the system axis and that of reflected emission off an ionized accretion disc around the supermassive black hole. The code successfully delivers the light curves of both components as observed at infinity. The light curves can be binned into different energy bands and then, by applying a Fourier transformation, the dependence of the lags (between the two energy bands) on time scale (i.e. on frequency) can be obtained. Several variable parameters have been included in the code in order to explore their effects on the lag-frequency spectra. These include the black hole spin (and obviously the system orientation), the primary emission spectral shape, the directionality of both the primary and reflected emission and so on.

While the first code was concentrating only on the frequency-dependence of soft lags in the topic of X-ray reverberation mapping in AGN, the second one (KYNrefrev code) brings the modelling into a higher level, by including the reverberation lags energy dependence, and by providing a full spectral-timing reverberation model suitable for fitting the data inside the widely used spectral-fitting package XSPEC. The code was entirely rewritten in C language so that it can make use of multi-thread computing not only outside, but also within the XSPEC fitting package. The major achievement of the new code was that it enables us to have full energy and frequency dependent products of Fourier transform of the time dependent spectral response. The spectral response is computed for the reflection scenario in the lamp-post geometry. The primary radiation, is reprocessed in the disc and again emitted in the form of reflection spectrum that is taken from Ross & Fabian (2005), available in XSPEC as the “reflionx.mod” table model. The code has been further optimized and several improvements have been included with respect to the first version ranging from a better geometrical sampling of the accretion disc (using a mix of log and linear steps) to a more flexible choice of the reference band to be used to compute the lags.

WP 7: Soft X-ray lags in AGN: data exploitation

Main aim of this work package was to exploit the X-ray data archives to characterize observationally the properties of the detected soft X-ray lags in individual AGN and, by a suitable stacking procedure, in the AGN population at large. Specifically: to search the extensive ESA observatory XMM-Newton data archive for high quality X-ray light curves of variable AGN with the goal of covering the widest black hole mass range; to apply the theoretical models developed in WP6 to X-ray data with the goal of unveiling the relative location and dynamical state of the source of the irradiating flux and the reflecting medium; to make use of the correlations between the lag observables and the AGN properties (most importantly the black hole mass); and to devise a suitable stacking procedure for combining lag versus frequency spectra.

We performed an extensive search of X-ray time-lags from observations in the XMM-Newton archive. All data where the observation length and source variability were great enough were included in the study (the main findings are summarised below). We explored both the soft and hard lags as a function of energy and we found new reverberation lag detections in several sources. This extensive exploration of the archive meant we could explore other aspects of the timing data, such as coherence and covariance, providing a more informative view of the variable emission components and aiding in the theoretical modelling of such time-lag data.

We were working on modelling the lag-frequency and lag-energy spectra using transfer functions that involved all the effects of general relativity (GR; see WP6). The GR transfer functions were applied to the sources with well defined iron Kα lags, and provided insight into black hole spin and the coronal properties. New and substantially longer XMM-Newton observations revealed the presence of a variable wind which has made modelling the time lag features more problematic than anticipated.

Finally, we have focused on exploring the wealth of information in the high frequency X-ray timing data to better understand the reverberation process. We have also explored the time lags associated with the X-ray quasi-periodic oscillation (QPO) phenomena, including a new QPO detection.

We have been extremely successful in obtaining large observations needed to explore X-ray time-lags (due to the Fourier frequencies where the time lags occur relative to the observation length). In the XMM-Newton AO15 target allocation we were awarded 1.5 Ms of time on the NLS1 galaxy IRAS 13224-3809 (PI Fabian), where the flux-dependent time-lags had already been observed.

Highlights

A global look at X-ray time lags in Seyfert Galaxies, Kara, Alston et al (2016).

In this work, we expanded the study of X-ray reverberation to all Seyfert galaxies in the XMM-Newton archive above a nominal rms variability and exposure level (a total of 43 sources). Approximately 50 per cent of source exhibited detectable iron K reverberation. We also found that on long timescales, the hard band emission lags behind the soft band emission in 85 per cent of sources. This ‘low-frequency hard lag’ is likely associated with the coronal emission, and so this result suggests that most sources with X-ray variability show intrinsic variability from the nuclear region. We updated the known iron K lag amplitude vs. black hole mass relation, and found evidence that the height or extent of the coronal source (as inferred by the reverberation time delay) increases with mass accretion rate.

The remarkable X-ray variability of IRAS 13224-3809, Alston et al (submitted).

Our new 1.5 Ms XMM-Newton observation has allowed us to explore the variability properties of one of the most variable Narrow line Seyfert galaxies in unprecedented detail. Including archival data we have used 2 Ms in total. We have discovered the variability was behaving in a non-linear, non-stationary manner. We have detected soft X-ray time lags which have unprecedented frequency resolution. The hard and soft band appear incoherent with each other and is affecting the ability to recover iron K alpha time lags. This could be due to either complex changes in source geometry with time, or the variable wind component (see Parker, Alston, et al 2017, MNRAS, 469, 1553) is adding an additional source of incoherent variability.

WP 8 and 9: Multiwavelength polarized variable emission of Sgr A*

The main aim in these work packages was to probe the strong gravitational field around SgrA* using simulations and observations of the multiwavelength polarized variable emission. Due to the progress in the field in the course of the project, we also include the study of two more physical phenomena: i) monitoring SgrA* during the G2/DSO fly-by, and ii) measuring the relativistic effects in the S2 orbit.

Sgr A multiwavelength emission*

Sagittarius A* (Sgr A*) at the center of our Galaxy is a highly variable near-infrared (NIR) and X-ray source which is associated with a supermassive black hole (see discussion in Eckart+2017) at the center of the Milky Way. In Parsa+2017, we presented the most up-to-date simultaneously obtained estimates for the mass of and the distance to Sgr A*. Using the three stars with the shortest orbital periods (S2, S38, and S55) and based on Newtonian models, we found M_{BH} = (4.15±0.13±0.57)×10^6 M_{sun}, and R_0 = (8.19±0.11±0.34) kpc. Sgr A* is always visible in the radio to longer mid-infrared domain. In the quiescent phases, it is currently below the detection/confusion limit in the NIR to X-ray domain, while during its flare phase, it can be observed in all spectral domains. The timescale of the flux-density variations indicate that most of the emission arises from the innermost region of the accretion flow around Sgr A*.

We compiled and analysed polarised NIR light curves of Sgr A* from 2004 -2012 to derive information on its radiation mechanisms and source geometry (Shahzamanian+2015ab). Sgr A* is strongly polarized in the NIR with typical polarisation degrees of 10–20% and a preferred polarisation angle of 13° ± 15°. The distribution of polarized flux-densities is consistent with the single-state power-law distribution (slope of ~4) derived by Witzel+2012 for all NIR data. These facts indicate that the source geometry and the energetics of the accretion process within the Sgr A* system are quite stable. The preferred NIR polarisation angle may be associated with the jet components close to or at the foot point of the jet.

The polarised NIR flares often exhibit X-ray counterparts. Short term variability is often explained by hot inhomogeneities formed in the mid-plane of the accretion flow as seen in GRMHD simulations (e.g. Moscibrodzka+ 2017). The characteristic ligh-curve of such orbiting hotspots shaped by the BH lensing and the boosting can be observed in bright X-ray flares. As the main result of this project, we produced a GR ray-tracing code capable to handle polarization of the emitting source (Bursa 2017). Using this code, we model all Sgr A* X-Ray bright flares showing that the asymmetric shape of the light curves is the result of an interplay of relativistic effects: Doppler boosting, gravitational redshift, light focusing, and light-travel time delays (Karssen+2017). We present a new method to derive BH masses from the light curves and successfully apply it to the Seyfert I galaxy RE J1034+396. As an extension of the code, we create two more implementations: i) an approximation to the light propagation in the optically thick case regime, and ii) plasmoid ejections from the accretion disk. The later allowed us to model the multi-component helical jet of M87 (Britzen+2017). The code and pre-computed tables were made publicly available.

Sgr A* NIR flares usually precede by few hours those at submillimeter (sub-mm) and radio regimes. A detailed statistical analysis of the 345 GHz sub-mm and the 100 GHz radio emission of SgrA* shows that both flux-density distributions are also well described by power-laws with ~4 slope (Borkar+ 2016, Subroweit+2017). This strongly suggests that radio-to-NIR flares arise from the same source components. The initial synchrotron turn-over frequency lies between 100–350 GHz, with negligable contribution from other frequencies, and the source expansion velocities are ~0.01c. To determine the nature of some of the sub-mm flux-density excursions, we performed Sgr A* NIR triggered mm-VLBI observations at 43 GHz (Rauch+ 2016). We could follow the Sgr A* source structure during the flare. Close to the peak time of the radio flare, Sgr A* showed a secondary component at ~1.5mas toward the SE of the core position, which would be consistent with relativistic bulk motions of the expanding source. Hence, it could be a jet or an outflow component.

The sub-mm flux distribution over the central parsec mapped at ~0.5" resolution using ALMA (Moser+2016), revealed a varying synchrotron spectral index ($S \propto \nu^{\alpha}$) in the inmediate vicinity of Sgr A*. In the frequency range 100-250 GHz the spectral index is α=0.5 and in the 230-340 GHz interval we find α≈0.0. At frequencies >350 GHz, the spectral index drops. In this regime, other regions, like the CND that acts like a barrier for the Galactic Center plasma (Mossoux and Eckart 2018), show continuum emission from Bremsstrahlung (α≈-0.1).

Monitoring the Dusty S-Cluster Object

The Dusty S-Cluster Object (DSO) is orbiting Sgr A* on a highly excentric orbit with a periapse in May 2014. Because of its bright NIR L-band and Brγ emission, it was proposed to be a gas+dust cloud that would tidally disrupt when passing near to SgrA* (Gillessen+2012, Pfuhl+2015). In contrast, we detect the source in K-band continuum (Eckart+2013, 2015), and compact before and after periapse (Valencia-S+2015). Besides, its high degree of linear polarization indicates a non-spherical configuration of the scattering material surrounding the object (Shahzamanian+2016, Zajacek+2017ab). These findings point to a stellar nature of the source, possibly a pre-main sequence star. No effects on the Sgr A* activity from radio-to-Gamma rays have been observed as a consequence of the DSO fly-by, with the exception of Ponti+2015 who reported increase in the number of X-Ray flare events, but the authors also indicate this could be purely due to a sampling issue.

*Hints for relativistic effects near to Sgr A**

Close to a supermassive black hole the GR effects on the stellar orbits start being appreciable. We use NIR VLT and Keck data to re-construct the orbit of S2, which has a short orbital period and high excentricity. The deviation of a first-order post-Newtonian orbit from a Keplerian one can be seen as the changes of orbital parameters, such as the semimajor axis, eccentricity, and the argument of periapse. The semimajor axis and eccentricity change when comparing the upper and lower halves, and the argument of periapse changes when comparing the pre- and post-periapse halves of the orbit. In Parsa+2017, we find the relativistic parameter, i.e. the inverse of the periapse distance (measured in Schwarzschild radii), to be Υ=0.00088 ± 0.00080. The theoretical expectation for S2 is Υ=0.00065. While the results can certainly be improved through the upcoming interferometric measurements in the infrared, it is the first time that a relativistic parameter could be obtained from stellar observational data.

WP 10: Modelling thermal X-ray continuum of accretion discs

The objectives of this workpackage were: to try to improve on the detailedness of the underlying physical models of thermal emission of stellar-mass black-hole accretion disks and to improve on accuracy of the modeling with respect to observational evidence.

We first focused on the assessment of how much difference there was in assumptions that existing thermal emission models (thin disk based) make in comparison with newly developed or improved models (slim disk based), in which some of those simplifying assumptions are relaxed. We checked how much irradiation comes to the disk as a function of luminosity and calculated spectra of such an irradiated disk, for which we developed a numerical code. The results were compiled to a FITS file that was accompanied by a corresponding XSPEC model.

Then we worked on the development of an XSPEC model of thermal disk radiation at super-critical accretion rates. The motivation for this work was that many ULX sources are believed to accrete matter at rates that are close to Eddington limit or higher, but the XSPEC modeling of their spectra (often using DISKBB + NTHCOMP models) is far from realistic. Our new model is based on slim disk solution to the radial structure of the disk, uses the expected geometrical extent of the disk with all associated effects (like self-obscuration of parts of the disk) and includes some loss of energy through advection. The model shall give much better BH mass and especially mass accretion rate estimates for ULX sources that take into account advection and inclination (beaming) effects.

Highlights

1. A numerical code for computing detaild thermal spectra of thin and slim accretion disks including the effect of irradiation.

2. A FITS table with a grid of irradiated thermal spectra, which can be used as an XSPEC table model for fitting.

3. A numerical code for calculating thermal spectra of super-eddington accretion disks.

4. An XSPEC model for fitting the super-eddington spectra to ULX sources (SLIMULX).

WP 11: X-ray reprocessing in the vicinity of black holes

The main objective of WP11 was to built a coherent model of the radiative transfer between geometrically thin accretion disks and their coronae in Black Hole X-ray binaries. It was intended to combine the computation of disk reprocessing together with calculations of the Comptonized emission from the corona while including Special and General Relativistic effects due to the black hole. To achieve this goal it was necessary to combine several radiative transfer codes and table models produced by the project. The two key ingredients of the modelling in WP11 were: 1. a complete set of disk reprocessing models for ionized accretion disks computed by the codes STOKES and TITAN, 2. a fully functional version of the MoCA code conducting relativistic transfer. The first goal had to be changed with respect to the initial plan of the project: shortly after the project started, the reprocessing model XILLVER was published and made it redundant to produce our deliverable in its original form. We thus decided to develop a more ambitious model that could be simultaneously applied to high resolution spectroscopy, timing and polarimetry observations. This change was in line with the forthcoming high-resolution X-ray satellites ATHENA and HITOMI/Astro-H2, and with the launch of the Imaging X-ray Explorer (IXPE) in 2021.

Highlights

The following results were obtained:

1. A full set of STOKES reprocessing models for an irradiated accretion disk with low disk heating has been completed. A careful set of tests was done to ensure the correctness of the thousands atomic data lines implemented. The reprocessed emission was computed as a function of both reemission angles as well as the incident angle, ionization parameter, spectral resolution and spectral index of the disk irradiation.

2. A grid of geometry-dependent coronal emission was produced by MoCA. Results have been obtained for a range of black hole spin and accretion rates to be compared to X-ray binaries. The combined spectral model was put into fits format so that it can be implemented in spectroscopic analysis tools such as XSPEC or SPEX.

3. An extension of the results towards supermassive black holes was achieved in order to probe black holes over the whole mass range. The impact of parsec-scale absorption, scattering and re-emission was assessed and clearly showed that radiative coupling between media that are orders of magnitude different cannot be neglected.

WP 12: Black-hole spin measurements – galactic black holes

The main aim was to exploit archival and new X-ray data to measure the spin of the galactic black holes using currently available tools and at a second step the models developed inside this FP7 project with the goal to study the corona-disc interactions and when possible to measure the black hole spin as precisely as possible.

Using the publicly available tools to spectral fits X-ray binaries in high/soft, low/hard and very high states.

The UCAM team has been involved in several works related to spin determination in classical X-ray binaries, both theoretical and observational in nature. They used new and archival data from NUSTAR, Swift, Suzaku and XMM-Newton. Spectral models widely available to the X-ray community have been used. In particular, Andy Fabian has been involved in developing the most recent relativistically blurred X-ray reflection models with a lamp-post geometry of Garcia et al (2013, ApJ, 768, 146) and Dauser et al. (2013, MNRAS, 430, 1694) to determine spin in accreting sources. Notably, in Fabian et al (2014, MNRAS, 439, 2307), it was shown that robust spin measurements require that at least part of the corona lies less than about 10 gravitational radii above the black hole in order that the innermost regions, including the innermost stable circular orbit (ISCO), are well illuminated. These limitations are particularly important at low Eddington fractions (e.g. the low/hard state) where the height of the corona may be relatively large, or outflowing, and tied to jet production. In Dauser et al. (2014, MNRAS, 444, L100) the role of reflection fraction on spin determination in the lamp-post geometry was considered. This is the ratio in flux between the direct and the reflected radiation, and is determined directly from the geometry and location of primary source of radiation. It was shown that high reflection fractions in excess of two are only possible for rapidly rotating black holes. Applying the additional constraint that the reflection fraction is at the maximum value possible for a given spin revealed that in this way unphysical solutions can be excluded and better constraints on spin could be obtained. In Parker et al (2015, ApJ, 808, 9) the first NuSTAR observations of Cygnus X-1 was presented in the hard state and investigate the disc truncation whilst the source was in the most luminous part of the hard state. It was demonstrated that the iron line required a relativistically blurred profile in combination with a narrow line and absorption from the companion wind. The modeling of the relativistic blurring of the iron line reveals that it required a high degree of smearing, with a high spin ($a>0.97$) and small inner radius ($r_{in}<1.7\ r_{ISCO}$), as well as a low source height ($h<1.56\ r_{ISCO}$). This rules out significant truncation of the disk at the transition to the hard state. In Parker et al (2016, APJL, 821, 6) reflection modelling of the very high state of GX 339-4 was performed using NuSTAR and Swift. Relativistic reflection modeling was used to measure the spin of the black hole and inclination of the inner disk, and a spin of 0.95(+0.02−0.08) and inclination of 30±1 degrees were inferred.

Mari Kolehmainen (CNRS) investigated the fundamental properties of X-ray binaries through accretion and ejection mechanisms. She studied Swift J1753.5-0127, a rather peculiar source in both radio and X-ray frequencies for which evidence of a break from the typical radio/X-ray correlation in this source was found, with the most likely physical interpretation of this behaviour to be a change in radiative efficiency as the source decreased in X-ray luminosity. She has also been involved in the study of the full spectral energy distribution from radio to hard X-ray frequencies which revealed evidence of two thermal components. This, combined with the lack of reflection features, would imply a possible presence of a two-component accretion disc with a gap in the middle (Tomsick et al. 2015, ApJ, 808, 85). The second part of the project at CNRS was a wider study of measuring the black hole spin in stellar-mass black hole X-ray binaries. This works included collecting of archival data of all available sources using a new catalogue (BlackCAT) including 59 objects. From Mari archive data mining, out of these sources, 33 currently have a distance estimation available, of which roughly half have available X-ray spectra. The spectral fits of these sources using the current available tools have been already performed.

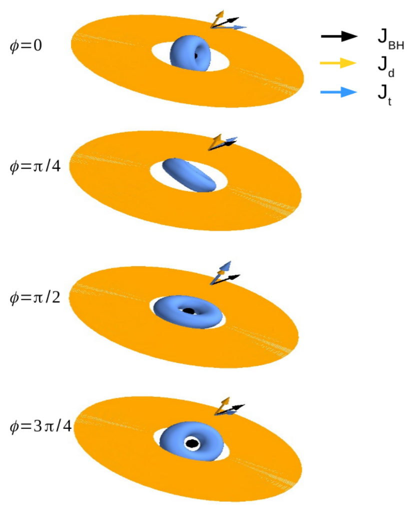
Using the SLIMULX code developed inside WP11 allowing the spectral fits of thermal spectra of slim discs around stellar mass black holes in the super-Eddington regime.

Regarding the suggestion that Ultra-Luminous X-ray sources (ULX) are accreting stellar mass black holes at unusual super-Eddington regime rather than Intermediate Mass Black Holes (IMBH) with 100s-1000s solar masses, this scenario has been tested with X-ray data currently available. Maria Caballero-Garcia (AsU) tested the model SLIMULX for the fit of thermal spectra of slim discs around stellar mass black holes in the super-Eddington regime, which consistently takes all relativistic effects into account. The developement of this code was supervised by Michal Bursa

(AsU) in the framework of this FP7 project in the WP10 ("Modelling thermal X-ray continuum of accretion discs"). They analysed the best available X-ray data from one of the prototypes of the ULX classification, NGC5408 X-1, which is located in a close-by (4.8 Mpc) small size starburst galaxy. NGC 5408 X-1 is very bright with a peak X-ray luminosity of about 2×10^{40} erg/s in the 0.3–10 keV energy range. It is noteworthy that previous spectral analysis using several phenomenological models had led to inferred an inner disc temperature of about 0.17 keV that would correspond to a black hole mass of about 2000 solar masses, that is, a IMBH (Caballero-Garcia, Belloni & Wolter 2013, MNRAS, 435, 2665). In contrast, applying the SLIMULX code, they found that a thermal disc black body model component taking into account all the relativistic effects describes the data well and gives a mass consistent with a stellar mass black hole (5.7±0.3 solar masses) accreting at a level above Eddington (Ldisc/LEdd=2.9±0.4). This is a very important result for our knowledge of the nature of ULX but this also demonstrates how the SLIMULX code developed in this FP7 project is crucial to securely discriminate between both possible origins of ULX: i.e. stellar mass black hole accreting at super-Eddington regime versus IMBH accreting at sub-Eddington regime.

WP 13: Fourier resolved spectroscopy for QPO

The goal of WP13 was to investigate the phenomenon of X-ray quasi-periodic oscillations (QPO) using methods of spectral and temporal analysis. A particular model for low frequency QPO was considered – the Lense-Thirring precession model. Its predictions were studied and compared with observational data.



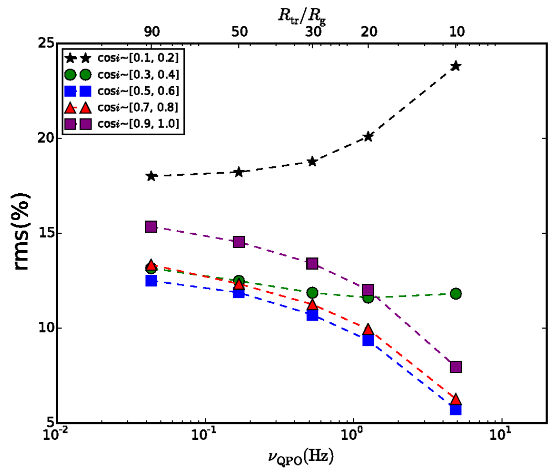
The Lense-Thirring precession model adopts the same general geometry as the standard model of hard spectral state of accreting black holes, where the hot plasma emitting hard X-rays forms an inner accretion flow, with the standard accretion disk outside of certain transition radius. The outer disk – approximately a Shakura-Sunyaev disk – produces the soft seed photons for the inverse Compton upscattering – the radiative process generating the hard X-rays. Some of these then illuminate back the outer disk producing the reflected/reprocessed component, which includes the reflection hump and the Fe K_α emission line near 6-7 keV.

In the adopted geometry the *variability* of the observed emission results from changing geometry (viewing angle) of the hot plasma relative to the distant observer and from the changing intrinsic conditions in the source. The latter include the temperature and optical depth of the plasma and the properties of the reflected/reprocessed component, resulting from the changing relative geometry of the two phases of accreting plasma.

Photons in the system propagate in the curved spacetime around a rotating black hole. This introduces Doppler energy shifts and additional distortions to the observed flux from the source, generally enhancing the observed variability.

Based on the above considerations a Monte Carlo code was written to simulate the spectra and time variability of the X-ray emission from such a precessing torus configuration. The code incorporates the considered torus+disk geometry and the inverse Compton upscattering as the basic radiative process responsible for generation of the hard X-rays. The Compton upscattering is implemented in the standard way described in the literature and thus includes the full Klein-Nishina cross-section for electrons drawn from a Maxwellian distribution of an assumed temperature. The soft seed photons originate from the external disk and are thus drawn using probability distributions corresponding to radial energy dissipation for a Shakura-Sunyaev disk, an assumed law of limbdarkening and axial symmetry of the disk. A fraction of emitted photons hitting the torus is then noted, in order to determine the total emergent spectrum.

For the hard X-rays produced in the torus illuminating the outer disk their impact point is noted and the reprocessing is simulated, again with a separate Monte Carlo type code, taking into account Compton scattering appropriate for cold electrons (but again with full Klein-Nishina cross-section), and photo-absorption for Solar abundances of heavy elements, with a possibility of the fluorescent emission of the iron K_α line at 6.4 keV. Relativistic effects on photon propagation were implemented using the sim5 library developed at AsU.



The basic result of the simulations is the sequence of spectra during the full period of a QPO, which can be analyzed using standard methods of spectral-temporal analysis. The most important observable is the energy dependence of the rms variability. This shows the general agreement with observations, in the sense that the model predicts variability of the hard Comptonized component, as indeed observed. The predicted amplitude of variability, at the level of ~10% is roughly what is observed. The exact forms of model rms(E) are less smooth than the observed dependencies, as can be expected from a models which is still simplified in terms of the plasma density structure. Finally, the summary of the obtained results is shown in the Figure – the dependence of the rms(E) amplitude on the transition radius of the accretion flow, which translates into the frequency of the QPO. Also, the dependence on the viewing angle, shown in the Figure – that high inclination sources show larger rms(E) – confirms the data, at least in the frequency range 1-10 Hz.

4.1.4 Potential impact, main dissemination activities and exploitation of results

The objective of STRONGGRAVITY has been to develop analytical tools to study processes occurring near astrophysical black holes, acquire observational data on the Galactic solar-mass black holes in binary systems, super-massive black holes in the centres of galaxies and our central black hole of the Milky Way, and use the created tools together with the new and archival data for better understanding the properties of black holes and their immediate neighbourhood.

Over five years of the project duration, StrongGravity has made a number of significant achievements and has produced many important results.

We have been developing new methods and analytical tools that are set off to be used with the observational data to model physical properties of active galaxies, Milky Way's central black hole or black holes in binary stars. Those tools are finished and have been released publicly with a free license and including all source codes to the benefit of the whole astronomical community. In addition, the members of the project have every intention to maintain those tools and improve them in subsequent years. Our codes predict shapes of spectra of radiation that comes from a hot corona surrounding black holes as well as how this radiation is reprocessed by reflection from the surface of an accretion disk. We also compute variability patterns from which we can reconstruct physical properties of the corona from the observed reflected radiation. Other codes deal with modelling characteristics of ambient gas media in accretion disc winds and warm absorbers with the aim to uncover their column densities, inclinations, distances and speeds. The sparse flares that are produced by the super-massive black hole in the center of our galaxy are modelled with our polarimetric code with the aim of constraining spin and inclination of the central black hole and learn about the mechanisms and the geometry of the emitting region. We have also prepared tools that help to exploit the capabilities of the currently planned space missions that will have unprecedented energy resolution. Our extensive computations of reflection atomic spectra provide a unique insight into the detailed spectra with unparalleled energy resolution that matches the resolution that Athena, the future ESA space telescope for X-rays, will provide.

Our second main focus has been on data exploitation. We have acquired observational data from numerous instruments both ground-based and space-born and this newly obtained data has been completed with archive data when needed. We have been largely successful in securing observing time at some of the most powerful X-ray and infrared instruments like XMM-Newton, NuStar or VLT telescope and Large Binocular Telescope to gather the top-class data of sources of our interest. Those data together with the archive data have been then analysed using the tools that we have been developing and we have already published some important findings. We have detected and announced for the first time a hint of a change in orbits of stars in the close vicinity of Galaxy's central black hole that is supposed to arise as a consequence of the supermassive black-hole gravitational field and the predictions of Einstein theory of gravity. We have discovered an ultra-fast winds reaching speeds of nearly a quarter of the speed of light and blowing gas out from another supermassive black hole in a distant active galaxy. These winds are important to study because they are able to clear the surrounding gas away from the black hole and therefore to suppress the birth of stars in the galaxy. This finding was only possible because we managed to secure an extraordinary long observation of the source on the ESA XMM-Newton satellite, which focused on the black hole for 17 days straight, revealing the extremely variable nature of the winds.

In accordance with our commitment to "use the analytical tools provided by our project in the preparation of the ESA mission projects and to provide accurate simulations for the scientific performance of next generation space-based X-ray observatories," we have contributed to the successfully accepted proposal of the new X-ray mission Athena, which will be the next big thing in X-ray astronomy once launched (almost half of the researchers from our consortium are involved), and to other smaller proposals for X-ray/polarimetry missions (Loft, Xipe, Ixpe, Xilpe, PolStar). We also contributed to development of infrared spectrometer instruments for both James Webb Space Telescope and for the European Extremely Large Telescope.

The consortium has so far published more than 170 papers in peer-reviewed scientific journals and other publications will still follow after the end of the project. The results have been presented on more than 300 occasions at scientific conferences and workshops. Beside of that there has been a strong encouragement in public outreach – the project has been presented in several national TV news and shows, on radio and in popular magazines. Several public lectures have been given to spread the knowledge and excitement to the civil society. A special section on the project web page is devoted to public outreach and explains the fundamentals of black-hole physics and accretion and another section is dedicated to astrophysical community to spread the codes developed by our consortium. We have made an effort to produce movies/apps that help to illustrate some effects of strong gravity. One example is an animation of the reverberation signal - a technique, which is one of the few ways we learn about black holes and accretion disks. Second example is a black-hole spacetime simulator that shows how light travels close to the black hole horizon. The later has been shown at a public exhibition and at the Science Fair, where it was seen by some 4000 people. We have also had 3 major international press releases (2 ESO, 1 ESA) covering our involvement in observation of active galaxies and the center of our galaxy. These press releases present outstanding observations and results of their analysis.

The project helped to educate a number of students who had a chance to work with more experienced colleagues on various interesting topics. This is quite an important aspect as those people (or at least a major fraction) will continue their carries in astronomy and deliver some more outstanding results. During the projects, twelve students have finished their MsC/PhD theses.

The StrongGravity project has brought together theoreticians and observers from seven different European countries with the goal of joining and coordinating efforts and producing a significant leap forward in the understanding of strong gravity effects around black holes.

In particular, we aimed at obtaining the most reliable methods of measuring black-hole properties in both stellar-mass and super-massive black holes. This objective has been reached by a combination of theoretical/computational and observational efforts.

We have develop new tools for the computation of the spectral, timing and polarization properties of the radiation emitted close to the black hole. These tools include all relevant physical processes at work in these systems, to account for the effects of general relativity on the properties of the radiation, and the further modifications due to the interaction of photons with matter in the surroundings of black holes. Those tools help to determine the best signatures of GR effects, separating them from other effects. The tools have been made compatible with pre-existing public data analysis packages, so that they can be used freely by the community at large.

We have also applied the tools to data (either from the public archives or obtained via dedicated proposals) mainly from current and near-future X-ray satellites. In particular, the data from European Space Agency (ESA) satellite XMM-Newton (whose scientific products and archives are maintained at ESAC) have been heavily exploited. We were able to largely improve upon our knowledge of the strong gravity effects around black holes across the range of masses. In addition to that, we have provided accurate simulations for the scientific performance of next generation space-based X-ray observatories as they are currently considered or accepted for building by ESA.

The project has contributed to fundamental science in astrophysics, and the main exploitation/dissemination of the results has consisted, as customary for this kind of research, in scientific papers published in international refereed astrophysical journals, in presentations at international conferences and in published software tools for free use. Our results are thus going to be spread in the scientific community by the usual channels; they already have and still will trigger new discussions in our field, and thereby give additional drive to the scientific progress.

It is important that our modelling and observational analysis can be tested and possibly extended by other research groups. Therefore all the computational tools are made available for everyone with free license and complete source codes. We are certain that our tools are going to be used outside of our collaboration as well and we presume that they give rise to new developments or even scientific ideas in Europe and elsewhere.