Final scientific report

“Studies of celestial radio sources at the highest angular resolution” (2012–2016)
National Research, Development and Innovation Office, project identifier: OTKA K 104539

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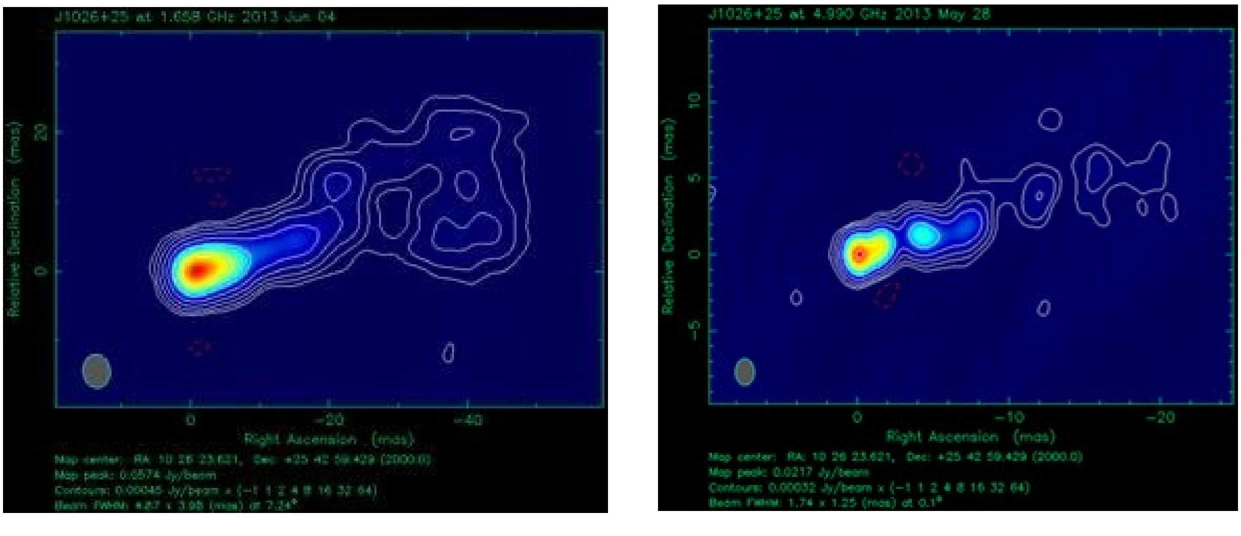
Introduction

This project was a continuation of the successful OTKA K 72515 project (2008–2012). We studied selected problems related to extragalactic astrophysics and astrometry, dominantly using the state-of-the-art technique of radio interferometry. The project helped maintaining the activities of a small but internationally recognised group, and allowed us to take part in educating the next generation of researchers. We consider a great success that three of the MSc students supervised are now pursuing their PhD studies, all in the field of radio interferometry (two of them abroad, one in Hungary). In the course of the project, we published more than 20 refereed journal papers, with a cumulative impact factor exceeding 150. Below we give a brief summary of the most important scientific results and other achievements related to the project, and give an account of our education and popularization activities.

Scientific results

One of our main aims was to study the **most distant radio-loud active galactic nuclei** (AGN) with the highest angular resolution provided by the technique of very long baseline interferometry (VLBI). The AGN are known to be powered by supermassive black holes (SMBHs) that accrete material from their immediate surroundings. Their synchrotron radio emission is produced by jets of charged particles moving at relativistic speeds in strong magnetic fields. The mere existence of AGN harbouring billion solar mass SMBHs out to redshift z=6...7 (i.e. existing at less than 10% of the present age of the Universe) is itself an unsolved problem in modern astrophysics. We imaged the **third most distant radio AGN known** at present (J2228+0110, z=5.95) with the European VLBI Network (EVN). The weak radio source was successfully detected with a compact milli-arcsecond (mas) scale structure typical of AGN (Cao et al. 2014, A&A 563, A111). In this project, we also pioneered the multiple-phase-centre observing mode with the EVN that makes it possible to investigate larger fields of view (several arcminutes) using single telescope pointings but multiple passes of correlation.



EVN images of the quasar J1026+2542 at 1.7 GHz (letf) and 5 GHz (right) from Frey et al. (2015)

The quasar J1026+2542 (z=5.3) is unique at extremely high redshifts with a rich radio jet structure extended to ~10 mas scales (Frey et al. 2013, MNRAS 431, 1314). First-epoch VLBI imaging observations at 5 GHz available from 2006 allowed us to look for structural changes in the jet. We initiated new observations with the EVN in 2013. The second-epoch imaging provided a time baseline of 7.33 yr. In the rest frame of the source, due to the time dilation caused by the expansion of the Universe, this is just 1.17 yr. The estimated apparent proper motions are 0.09–0.11 mas/yr for three of the jet components. These correspond to superluminal apparent transverse speeds of ~11–14c. Such **jet proper motion estimates were made for the first time for any AGN at z>5**. The moderate component proper motions agree with what is expected in a relativistic cosmological model for a source at that high redshift (Frey et al. 2015, MNRAS 446, 2921).

We participate in an imaging mini-survey of **powerful radio quasars at z>3** using the technique of **Space VLBI**, involving the Russian *RadioAstron* satellite. The sample consists of 10 objects that are sufficiently bright for Space VLBI detection with a 10-m diameter orbiting radio telescope. The satellite was launched in 2011 and is still operational, although its observations are now hampered by technical issues. Also, its highly eccentric orbit with a period of ~9.5 days limits the time most useful for interferometric imaging to the short near-perigee sections of the orbit, and there is a large number of competing projects. A series of our observing proposals responding to the calls issued once every year, plus observing requests to various supporting ground-based VLBI networks – the EVN, the U.S. Very Long Baseline Array (VLBA) and the Australian Long Baseline Array (LBA) – were mostly accepted in the past couple of years. The observations granted to us are either scheduled, going on, or the data are waiting for correlation. The main goals of the project are measuring jet proper motions (using the earlier Space VLBI data from the 1990s and 2000s obtained by the Japanese HALCA satellite), to determine if the physical parameters of the objects are similar to those of low-redshift quasars, and to estimate the SMBH masses by measuring the jet cross-sections. Because of the complicated process of data acquisition and correlation, the project progresses slowly. Apart from reporting the preliminary analysis results of one quasar already observed (J0646+4451 at z=3.4) at a conference (Frey et al. 2014, 40th COSPAR Scientific Assembly, E1.10-0003-14), the overall results remain to be published after the project is completed.

We also participate in one of the Key Science Programs of the *RadioAstron* mission. This wide international collaboration (a group of 70 researchers led by Y. Y. Kovalev, Astro Space Center, Moscow) initiated a non-imaging monitoring **survey of the brightest radio AGN cores**. The full sample consists of about 250 sources. Significant detections on Earth–space baselines were found for more than 160 AGN, at at least one of the 3 observing frequencies (1.6, 5 and 22 GHz). The finest formal angular resolution achieved in the survey was ~14 micro-arcseconds (baselines of 15 Earth diameters at 22 GHz). This survey is an on-going effort, with substantial resources required from the space antenna and the participating ground radio telescopes. The aim is to measure the brightness temperature of AGN cores, to better understand the physical mechanisms of their emission. The survey already provided intriguing results, which appear to challenge our current knowledge of the origin of compact radio emission in AGN and the excess of Doppler boosting implied by jet kinematic measurements. Brightness temperatures are typically one order of magnitude higher than what was known before from ground-only VLBI, often reaching 10^{14} K. There is also an extensive parallel ground-based monitoring program of the survey sample sources for **intra-day variability** (IDV) caused by interstellar scattering, which provides another way of estimating brightness temperature. It is possible that the extremely high brightness temperatures are caused by refractive substructures introduced by scattering in the interstellar medium (Johnson et al. 2016, ApJ 820, L10). The *RadioAstron* AGN survey program is currently also in the phase of data accumulation, potentially high-impact results are expected to be published in the coming years.

In the course of our research project, we made an attempt to find a connection between the IDV of a large sample of extragalactic sources, and the molecular (CO) absorption in their direction, originating from the molecular clouds connected to photo-dissociation regions in the Milky Way.

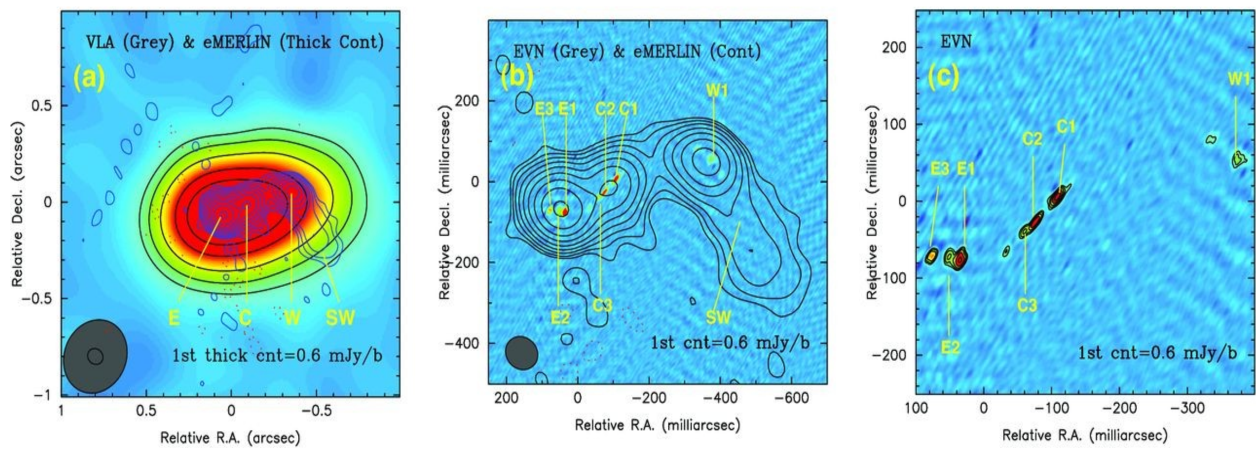
However, these studies proved inconclusive and the results were insufficient for publication.

Other main targets of our studies were the **dual and binary AGN**. (We call a system *dual* if the separation of the components are at kpc scale, and *binary* if smaller.) According to models of hierarchical structure formation in the Universe, merging galaxies are expected to be seen in different stages of their coalescence. Especially after the direct detection of gravitational waves in 2015, the existence and demography of such systems are of special interest, even though the ground-based gravitational wave detectors are sensitive only to stellar-mass black hole mergers. However, pulsar timing arrays are expected to be able to detect the stochastic background of low-frequency gravitational waves emitted by coalescing SMBHs in the near future. Studies of dual and binary AGN also provide essential inputs for galaxy evolution models.

Unfortunately, at present we don't know any straightforward observational method to reliably select or confirm a large number of dual AGN candidates. In the recent years, objects with double-peaked narrow optical [OIII] emission lines were regarded as promising candidates. In these AGN, the double-peaked lines may originate from the two different narrow-line regions surrounding each of the pair of AGN which orbit around a common mass centre. The difference in the line-of-sight velocities causes the shift in the line peaks with respect to the systemic velocity. However, other viable explanations for the phenomenon also exist, e.g. jet-driven outflows from a single AGN can also cause double-peaked spectral lines.

We studied various **AGN with double-peaked narrow optical [OIII] emission lines which are known radio emitters**. Since VLBI provides the finest imaging angular resolution among all astronomical techniques, it is the most promising way in terms of resolution to identify kpc-separation or even tighter AGN pairs, provided that both components produce jets at the same time and thus active in the radio. The series of our studies led to a mixture of radio structures in the different sources targeted. The overall results are generally consistent with the consensus emerging from the recent literature that only a small minority of double-peaked narrow-line candidates are actually dual AGN.

The most attention was attracted by the VLBI discovery of a **close AGN pair nested in a rare triple AGN system** (J1502+1115; Deane et al. 2014, Nature 511, 57). We participated in the study performed by the EVN and other radio instruments. This triple SMBH system is at z=0.39, the closest pair is separated by 140 pc (projected onto the plane of the sky) as resolved by VLBI. Remarkably, the presence of the tight pair is imprinted onto the properties of the large-scale radio jets as a rotationally symmetric helical modulation, which may provide a useful way to search for other tight pairs, without actually needing VLBI observations. VLBI offers extremely high resolution but is “expensive” in a sense that the narrow field of view makes the observing technique unsuitable for blind surveys.



Radio images of 3C 316 at three different resolutions, with the Very Large Array, e-MERLIN, and EVN at 5 GHz, from An et al. (2013)

We performed a detailed study of the prominent radio source **3C 316** using radio interferometer networks at various resolutions, from arcsecond to mas scales. This object shows double-peaked narrow optical [OIII] emission lines. Based on the complex S-shaped radio structure we found from the data taken with the British e-MERLIN network and the EVN, it appears that the emission-line peaks originate from jet–cloud interactions around a single AGN (An et al. 2013, MNRAS 433, 1161).

No evidence for two radio-emitting nuclei was found in the dual AGN candidate **NGC 5515**. Based on EVN data taken at two different frequencies, we concluded that a single AGN provides a more plausible explanation for the radio observations and the optical spectrum of this Seyfert galaxy (Gabányi et al. 2014, MNRAS 443, 1509). We observed **four other dual AGN candidates** which were considered especially promising since they were selected not only by their double-peaked optical emission lines, but additional criteria as well. Data taken with the VLBA at 1.5 GHz with ~10 mas resolution revealed that in two objects the radio structures are aligned with the optical emission features, thus the double-peaked emission lines might be the results of jet-driven outflows. In the third detected source, the radio structure is less extended and oriented nearly perpendicular to the position angle derived from optical spectroscopy. The fourth source remained undetected with the VLBA, suggesting the existence of extended radio structure. In summary, evidence for dual radio AGN could not be found in any of the four targets (Gabányi et al. 2016, ApJ 826, 106).

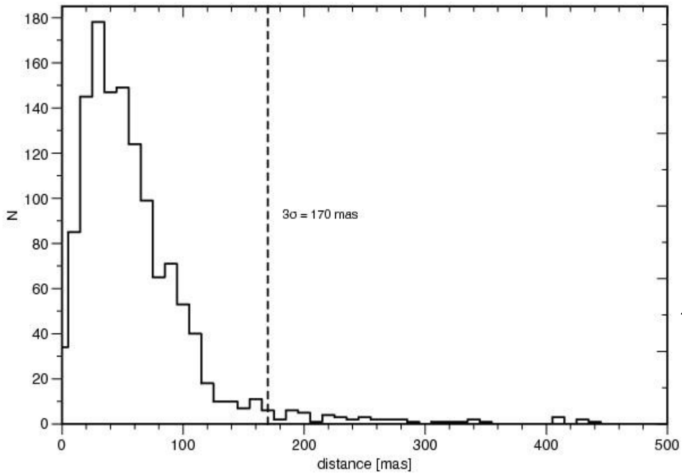
Zooming further into binary AGN which are not resolvable even with VLBI measurements, we took part in analysing the archival VLBA monitoring observations of the quasars S5 1928+738 (z=0.30) and PG 1302–102 (z=0.28). SMBH binaries are very difficult to detect directly, but the **helical radio jets** may offer an observable signature. These could be explained by the precession of the spin of the black hole responsible for jet launching. Long-term VLBI imaging data of S5 1928+738 (Kun et al. 2014, MNRAS 445, 1370) were analysed in the context of a geometric model of a helical structure. The jet components were interpreted as a result of the orbital motion of a binary black hole at the jet base. The binary mass ratio and the separation were estimated. There is indication of a slow reorientation of the spin of the jet-emitting black hole induced by the spin-orbit precession. The quasar PG 1302–102 came into the focus because of the recently discovered 5.2-yr periodicity of its optical light curve. It was proposed to harbour a sub-pc separation binary SMBH. The **pc-scale radio jet kinematics and kpc-scale radio morphology** of the source are broadly consistent with this picture. There is indication of a helical jet structure on kpc scale, but the directions of the inner and the extended radio jets are significantly different (Kun et al. 2015, MNRAS 454, 1290).

We analysed nearly 100 epochs of archival dual-frequency VLBI data of the high-redshift quasar S5 0014+813 (z=3.37), one of the most luminous AGN known. The observations cover a period longer than 20 years. We found tentative evidence of **jet precession** with a 12-yr periodicity in the observer's frame. The data can be adequately described with a simple kinematic model but longer-term monitoring is essential to confirm the periodicity (Rozgonyi & Frey 2016, Galaxies 4, 10).

Understanding the physical mechanisms of high-energy gamma-ray emission of AGN is a topical problem in current astrophysics. Often the simple identification of celestial **gamma-ray sources with counterparts** at other wavebands is difficult. Radio interferometric observations are of special value, because the AGN nature of an extragalactic source can be proven with a VLBI detection, and the positional accuracy achieved leaves no doubt about the exact coordinates of the object. According to our EVN observations, the second most distant AGN detected in the soft gamma-ray band with the INTEGRAL satellite, IGR J12319-0749 proved to be a compact blazar with highly Doppler-boosted jet (Frey et al. 2013, A&A 552, A109). The source Fermi J1418+3541 was imaged with EVN shortly after its gamma-ray outburst. Our results support the blazar nature of this object as well (Frey et al. 2013, ATel 4750).

Our most puzzling high-energy target was the TeV gamma-ray source **HESS J1943+213**. Its identification was rather uncertain after its discovery with one of the ground-based Cherenkov telescope arrays (H.E.S.S.). Its position very close to the plane of the Milky Way suggested that the source might be Galactic. Our radio imaging with the EVN and the analysis of the Galactic atomic hydrogen (HI) distribution towards the gamma-ray source direction left two options open. The accumulated evidence pointed towards an interpretation that HESS J1942+213 is a pulsar wind nebula within our Galaxy (Gabányi et al. 2013, ApJ 762, 63). Later, after the addition of new dual-frequency e-MERLIN observations, and with a negative result concerning a pulsar detection experiment performed with the Arecibo radio telescope, we concluded that the source is most likely an extreme BL Lac object, i.e. an extragalactic AGN source with atypical characteristics (Straal et al. 2016, ApJ 822, 117).

A major result in our project was an in-depth study of **optical–radio positional offsets** for AGN contained in both the latest release of the Sloan Digital Sky Survey (SDSS) and in the list of the VLBI-based International Celestial Reference Frame (ICRF2). The relevance of the work (Orosz & Frey 2013, A&A 553, A13) was to prepare for the coming new era of highly accurate optical astrometry promised by the Gaia spacecraft launched by the European Space Agency in 2013. For the first time, Gaia is able to directly connect the most accurate radio and optical reference frames that are established with comparable accuracy, by observing a large number of radio reference AGN in the optical. Indeed, just after the completion of our project, the first Gaia catalogue was publicly released in September 2016, accompanied by a paper to compare ICRF2 source radio coordinates with the Gaia data (Mignard et al. 2016, A&A, in press – arXiv:1609.07255; our study is cited in this work). Before Gaia, we used the best available data bases and showed that ~4% of the sample of nearly 1300 common AGN have significant differences in their position at the two wavebands. Potential astrophysical causes (gravitational lensing, dual AGN) were identified. Some of the outlier objects (whose entire list is published in the paper) will require follow-up radio interferometric or optical spectroscopic studies. This result has consequences for the future precise connection of the most accurate radio and optical celestial reference frames (for the selection of suitable link objects). The method could also hint on new dual AGN, recoiling AGN, or gravitationally lensed systems.



A histogram of optical–VLBI total positional differences for 1297 ICRF2 sources identified in the SDSS Data Release 9, from Orosz & Frey (2013)

Astrophysical black holes are mostly found in two basic varieties. Stellar-mass black holes are below a few tens of solar masses, while SMBHs occupy the range between $\sim10^6$–$10^{9.5}$ solar masses. The evidence for **intermediate-mass black holes** (IMBHs; between $\sim10^2$–10^5 solar masses) is still quite elusive, although much progress has been made in the last couple of years in the observational front. The only chance to directly detect IMBHs is if they are active, i.e. accrete material and produce radiation which is however scaled down with respect to the power produced by SMBHs. One possible hiding place of active massive black holes is the centres of nearby dwarf galaxies. These galaxies escaped from mergers over their whole lifetime and may harbour seed black holes below the SMBH limit. Moreover, their proximity may allow us to detect the faint sources with the current X-ray and radio instrumentation. With our deep EVN observations and non-detection, we did not find evidence for the proposed active massive black hole in the nucleus of NGC 404 (Paragi et al. 2014, ApJ 791, 2).

Usual candidates for IMBHs are the **ultraluminous X-ray sources** (ULXs). These are found in external galaxies as off-nuclear X-ray sources which don't reach the luminosity of AGN but clearly exceed the radiating power expected from stellar processes or stellar-mass black holes. Some of them may well be accreting IMBHs. To check that, radio interferometric observations can be invoked. From Very Large Array (VLA) data, we found that the ULX Holmberg II X-1 has a complex extended radio structure. This, together with X-ray data, suggests that the object is powered by a black hole of >25 solar masses, possibly with a renewed, intermittent radio activity (Cseh et al. 2014, MNRAS 439, L1).

With the essential participation of one of our students involved in the project (Fogasy), the nucleus of the prominent radio galaxy 4C 12.50 was studied, using VLBI data from a worldwide array of radio telescopes. From accurately localising the places of the atomic hydrogen (HI) absorption in the host galaxy, an evidence was found that the radio jets emanating from the nucleus effectively “clear out” the galactic cold gas from their way. This **feedback process** caught in the act in 4C 12.50 explains why many galaxies which have undergone nuclear activity, in the absence of the basic ingredients, stop forming new stars (Morganti et al. 2013, Science 341, 1082).

Other achievements

We contributed to the science case of the **Square Kilometre Array (SKA)**, a major next-generation global astronomical (radio interferometric) infrastructure, about to be built in the southern hemisphere. As a part of a large international collaboration involving the international VLBI community, we studied SKA's future role as a crucial element of global VLBI arrays [Paragi et al. 2015, PoS(AASKA14)143]. We also investigated the possibilities of surveying multiple SMBH systems in the future with SKA [Deane et al. 2015, PoS(AASKA14)151].

Thanks to this OTKA project which allowed us to continue our research activities, we could attract additional funds. In collaboration with the VLBI group in the Shanghai Astronomical Observatory of the **Chinese Academy of Sciences** (CAS), every year we successfully applied for the annual extension of our scientific exchange project financed by the CAS. Based on this fruitful collaboration, we could also launch a collaborative (NN) OTKA project in 2014.

By observing with the EVN and e-MERLIN facilities, we became eligible for certain funding for data reduction visits to European institutions via the RadioNet3 project supported within the **European Commission**'s 7th Framework Programme (FP/2007-2013).

Due to her excellent research performance, Gabányi won a Magyary postdoctoral **fellowship** in 2013 (TÁMOP 4.2.4.A). As an international recognition of our achievements in the field, Frey was nominated as an at-large **member of the EVN Program Committee** for a 3-year term (2014–2017). The committee consists of radio observatory delegates and at-large members representing the user community. This expert body evaluates the scientific proposals received by the EVN 3 times a year and defines the scientific strategy of the network. We hosted one of the regular meetings of the EVN PC in Budapest in 2015.

Education and popularization

We are committed to participate in educating the next generation of researchers and to introduce radio astronomy and the interferometric observing technique to students. We believe this is the best way to advance the field and to ensure the continuity of this perspective scientific area in a longer term. We also firmly believe that science popularization is an essential part of our work, therefore we made efforts to actively communicate our results to the general public.

Our **education** activities related to the project included lecturing and student supervision at different Hungarian universities, as follows:

- ***Eötvös University, Budapest*** *(astronomy)*

Radio astronomy (2 semesters, special course in English language for physics & astronomy MSc and PhD students; Gabányi, Frey, 2013/2014 and 2015/16)
BSc supervision (Frey; students: Ingrid Tar, Tibor Dávid)
MSc supervision (Frey; students: Judit Fogasy, Ingrid Tar, Krisztina Perger, Kristóf Rozgonyi)
Scientific Students' Associations (TDK) supervision (Frey; students: Judit Fogasy, Melinda Nagy, Ingrid Tar, Krisztina Perger, Kristóf Rozgonyi)

- ***University of Szeged*** *(astronomy)*

Radio astronomy (1 semester, special course for physics & astronomy MSc and PhD students; Frey 2013 / Gabányi 2014)
Relativistic astrophysics (1 semester, special course for physics & astronomy MSc and PhD students; Gabányi together with Z. Keresztes, 2014)
Observations of active galactic nuclei (1 semester, special course for physics & astronomy MSc and PhD students; Gabányi 2013)
PhD co-supervision (Gabányi; student: Emma Kun)

- ***Budapest University of Technology and Economics*** *(geodesy)*

MSc supervision (Frey; student: Tímea Asbóth, Barbara Gruber)
PhD co-supervision (Frey; student: Gábor Orosz)

Highlights of our **popularization** activities include various publications in online (e.g. csillagaszat.hu) and written media (e.g. Élet és Tudomány, Meteor) about our new results in Hungary. We were occasionally involved in preparing popular articles and press releases for international audience as well. Apart from regularly appearing at professional meetings in Hungary, we also gave popular lectures. Gabányi is maintaining a blog about AGN research at activegalacticnuclei.blogspot.hu.

Finally, we express our sincere gratitude for the project support which enabled us to achieve the scientific and other results summarized above.