Statement of research interests and accomplishments

Active galactic nuclei (AGN) and accreting white dwarf binaries (cataclysmic variables – CV) have many observational similarities revealing signatures of shocks, jets and accretion. This provides an opportunity to learn more about the physics underlying these phenomena.

The origin of AGN variability and AGN–CV similarities

Active galactic nuclei and specifically their jetted variety, blazars, change their brightness on timescales from minutes to decades, and we don't really understand why. There are fruitful ideas rooted in our general understanding of emission mechanisms acting in blazars. Variations in plasma density, motion direction and velocity as well as magnetic field strength modulate the non-thermal emission. Shocks traveling down a relativistic jet of plasma almost certainly play a role. The density and magnetic field strength variations are likely propagated to the jet from the accretion disk where small perturbations are amplified as they drift inward across the disk. The disk and jet interactions with the ambient diffuse medium, gas clouds and stars must play a role. While many pieces of the puzzle are at hand, we are still far from constructing a self-consistent picture of how the AGNs work and what specifically drives their brightness variations across the electromagnetic spectrum. A major complication is that the inner region of the accretions disk and the jet launching site are located deep within the gravitational well of a supermassive black hole, barely accessible to direct observations.

The ongoing attempts to solve the AGN variability puzzle head-on are important. What is often overlooked is that many aspects of our understanding of processes driving AGN emission and its variability may be tested in non-relativistic regime using Galactic accreting white dwarfs. Unlike CVs, neutron star/black hole X-ray binaries (including their jetted variety – microquasars) do not offer the advantage of being non-highly-relativistic systems.

Apart from accretion that powers both AGNs and CVs, ejection processes in these systems bear surprising similarities. Nova (an event of thermonuclear runaway at the bottom of a hydrogen-rich shell accreted onto the white dwarf) may drive strong shocks accelerating particles and emitting across the electromagnetic spectrum from meter-wave radio to TeV energies. Emission in such a wide energy range is typical for blazars (and is also found only in GRB afterglows, supernova remnants and the Milky Way Galaxy). Similar to blazars, novae are considered as potential neutrino sources. A tight correlation between optical and GeV γ-ray variations has recently been observed by our team in nova V906 Car – a feature commonly found in blazars. The shocks being the underlying energy transport mechanism important in both blazars and novae is the most likely physical basis for these similarities.

There are published reports of jets associated with novae and symbiotic systems (accreting white dwarf binaries with a giant donor). If these nova-associated jets are real at all, how common are they and how they are launched are the open questions. Radio emission observed from CVs not undergoing thermonuclear runaway and powered directly by accretion (dwarf novae and novalike systems) has been interpreted as a manifestation of jets. The extreme faintness ($\sim \mu$Jy) of radio emission from non-nova CVs has precluded us form getting detailed information (variability power spectra, resolved imaging) about jets in these systems.

Specific research opportunities and previous experience

The role of shocks in novae and other transients has been highlighted by the detection of GeV γ-ray emission of Galactic novae (Abdo et al., 2010; Ackermann et al., 2014). This emission is produced by non-thermal particles accelerated by shocks within the nova ejecta (Caprioli & Spitkovsky, 2014; Slane et al., 2015). The recent discovery by our team of *simultaneous GeV and optical flares* near the nova peak (Aydi et al., 2020) revealed that *shocks are responsible for more than half of nova bolometric luminosity.* Despite considerable theoretical efforts (Vlasov et al., 2016; Vurm & Metzger, 2018; Steinberg & Metzger, 2018; Martin et al., 2018), we still lack basic understanding of location, geometry and physical properties of the shocked region(s). A stunning example is the four orders of magnitude discrepancy between the predicted and observed hard X-ray brightness of GeV-detected novae (Sokolovsky et al., 2020, 2021).

Currently, I'm working on characterizing shock properties in novae through multiwavelength observations with the emphasis on simultaneously collected X-ray (*NuSTAR*, *Swift*/XRT, *XMM/Newton*) and GeV

(*Fermi*/LAT) data (Sokolovsky et al., 2020, 2021). I also regularly reduce the ongoing VLA monitoring observations of novae in radio band (Chomiuk et al., 2021). Earlier I was characterizing γ-ray-to-radio variability of an unusual non-blazar AGN GB 1310+487 (Sokolovsky et al., 2014). I will continue this work by analyzing already performed NuSTAR and multiwavelength observations of the two 2021 novae: V1405 Cas and V1674 Her.

In the future, I plan to coordinate multiwavelength (X-ray/optical/radio) observations of newly discovered GeV-bright novae with the aim of further constraining physical parameters of shocks within their ejecta. Novae expand our understanding of astrophysical shocks to higher densities and lower velocities, and are therefore relevant for other explosive shock-powered transients, including Type IIn and super-luminous supernovae, tidal disruption events, and stellar mergers (Metzger et al., 2015). It has long been speculated that shocks traveling down a relativistic jet are responsible for multiwavelength variability of blazars (Böttcher & Baring, 2019). While shocks in blazar jets emit non-thermally in all bands, shocks in novae emit thermal X-rays and (reprocessed) optical light while non-thermal emission is produced in γ-rays and radio. Investigating shocks in novae may provide new insights in blazar variability.

Shocks accelerate particles that produce high brightness temperature synchrotron emission. The technique of VLBI allows one to image synchrotron-emitting sources at sub-milliarcsecond scale – the most obvious targets being the regions responsible for variable radio emission in AGN. For my PhD thesis I used the VLBA to investigate frequency-dependent shift of the apparent AGN jet base confirming synchrotron opacity as the dominant mechanism responsible for this effect (Sokolovsky et al., 2011). Being part of *RadioAstron* Space-VLBI operations team I've contributed to direct detection of extreme brightness temperatures in AGN jets (Kovalev et al., 2016; Johnson et al., 2016; Gómez et al., 2016; Pilipenko et al., 2018) – a hallmark of in situ particle acceleration. The other *RadioAstron* result I've contributed to was detailed imaging of the nearly cylindrical edge-brightened jet in the radio galaxy 3C 84 (Giovannini et al., 2018; Savolainen et al., 2021). Relying on the AGN VLBI experience, I participate in ongoing VLBA programs aiming to reveal a spatial structure of shocks within a nova shell.

Flickering is stochastic variability characterized by a power-law power spectral density. It appears to be a common feature of accreting objects as diverse as young stellar objects (YSO), symbiotic stars and CVs, X-ray binaries and active galactic nuclei (AGN; Scaringi et al. 2015). The physical origin of flickering is unclear, but it is believed that flickering may be related to the modulation of accretion rate in the disk (Lyubarskii, 1997). Interacting binaries may have the hot spot (where the accretion flow from the donor star hits the accretion disk) as the secondary source of flickering Baptista & Bortoletto (2004). The presence of flickering in YSO, symbiotic stars and AGN (not expected to have an equivalent of the hot spot) suggests the flickering is often associated with the accretion disk.

Interacting binaries are useful models for understanding the nature of non-jetted AGN variability (Kelly et al., 2009) as they vary on convenient timescales and (in the case of CVs) are relatively free from relativistic effects. Constrains on the possible source and physical nature of flickering may be obtained from the *slope and features in the power spectrum* (Scaringi et al., 2012a,b), *time lags* between lightcurves at different bands Bruch (2015) and eclipse mapping Baptista & Bortoletto (2004). Good understanding of "normal" AGN variability, while being interesting in its own right, is also important for proper identification and interpretation of unusual events in galactic nuclei (Graham et al., 2017), including tidal disruption events, changing-look AGNs and supernova explosions close to a galactic center.

The analogy between AGNs and accreting binaries may work the other way too: many AGNs host synchrotron-emitting jets, so do many black hole binaries Körding (2014). One may wonder if the jet production is a common feature of all accreting systems? Observations suggest that CVs may indeed harbor synchrotron jets Körding et al. (2008, 2011); Coppejans & Knigge (2020). The Blandford & Znajek (1977) process thought to be responsible for launching AGN jets cannot operate with a white dwarf instead of a black hole. A Blandford & Payne (1982)-like processes may produce a CV jet. New observations suggest this process is at work in at least some AGNs (Giovannini et al., 2018).

Coordinated multiwavelength observations of various accreting systems (including timing, spectral energy distribution interpretation and direct imaging with VLBI) should put new constraints on accretion and jet launching physics. Determining how accretion disks and jets look across the widest range of central object masses and accretion rates is the necessary step towards physical understanding. Uniformly analyzing multiwavelength lightcurve of multiple Galactic and extragalactic sources will require development of a new computer code that would streamline such analysis. My previous experience with multiwavelength observations, variability detection and lightcurve characterization as well as high-resolution imaging in radio puts me in a good starting position to identify and follow accretion-powered transients.

Specifically, I have explored variable source identification techniques using variability indexes computed over lightcurves (Sokolovsky et al., 2017b) and combinations of indexes using statistics (Moretti et al., 2018) and machine-learning (Pashchenko et al., 2018). The techniques were implemented in my `VaST` code (Sokolovsky & Lebedev, 2018) and applied to datasets as diverse as digitized photographic plates (Sokolovsky et al., 2017a) and `HST` photometry (Bonanos et al., 2019). I developed codes for periodicity search in lightcurve[I] and photon arrival times[II] data.

New compact binaries may be found by combining GeV and X-ray catalogs with optical variability surveys (e.g. Strader et al., 2014; Schinzel et al., 2017; Miller et al., 2020). As the error radius of an unidentified high-energy source often includes many optical sources, the detection of variability may be the key to identification of the correct optical counterpart (e.g. Salvetti et al., 2017; Denisenko & Sokolovsky, 2011). The fourth Fermi catalog contains *hundreds of GeV sources that remain unidentified* despite considerable multiwavelength efforts. The sources imaged at the keV band have a better positional accuracy, but even smaller fraction of them have confirmed counterparts at lower energies. The currently available large X-ray catalogs include the reprocessed *ROSAT* survey (2RXS, Boller et al. 2016), the *Chandra* Source Catalog Evans et al. (2010), the *XMM-Newton* serendipitous Rosen et al. (2016) and slew Saxton et al. (2008) surveys, as well as the catalogs derived from *Swift* X-ray telescope observations (Evans et al., 2014; D'Elia et al., 2013) soon be complemented by *eROSITA* Predehl et al. (2016). I plan to search time-domain surveys (ZTF, Pan-STARRS, ATLAS, Catalina, Gaia) for variable sources and find among them new counterparts of unidentified GeV and X-ray sources. The identifications will be confirmed with dedicated optical and X-ray observations. The goal of this search is to identify many new accreting systems to aid in statistical analysis of their properties as well as to search for unique objects displaying new accretion/ejection regimes. Multiple undergraduate research projects may be formulated around the search for new compact binaries.

References

Abdo A. A., et al., 2010, Science, 329, 817
Ackermann M., et al., 2014, Science, 345, 554
Aydi E., et al., 2020, Nature Astronomy, 4, 776
Baptista R., et al., 2004, AJ, 128, 411
Blandford R. D., et al., 1982, MNRAS, 199, 883
Blandford R. D., et al., 1977, MNRAS, 179, 433
Boller T., et al., 2016, A&A, 588, A103
Bonanos A. Z., et al., 2019, A&A, 630, A92
Böttcher M., et al., 2019, ApJ, 887, 133
Bruch A., 2015, A&A, 579, A50
Caprioli D., et al., 2014, ApJ, 783, 91
Chomiuk L., et al., 2021, ApJS, 257, 49
Coppejans D. L., et al., 2020, New A Rev., 89, 101540
D'Elia V., et al., 2013, A&A, 551, A142
Denisenko D. V., et al., 2011, Astronomy Letters, 37, 91
Evans I. N., et al., 2010, ApJS, 189, 37
Evans P. A., et al., 2014, ApJS, 210, 8
Giovannini G., et al., 2018, Nature Astronomy, 2, 472
Gómez J. L., et al., 2016, ApJ, 817, 96
Graham M. J., et al., 2017, MNRAS, 470, 4112
Johnson M. D., et al., 2016, ApJ, 820, L10
Kelly B. C., et al., 2009, ApJ, 698, 895
Körding E., 2014, Space Sci. Rev., 183, 149
Körding E., et al., 2008, Science, 320, 1318
Körding E. G., et al., 2011, MNRAS, 418, L129
Kovalev Y. Y., et al., 2016, ApJ, 820, L9
Lyubarskii Y. E., 1997, MNRAS, 292, 679
Martin P., et al., 2018, A&A, 612, A38
Metzger B. D., et al., 2015, MNRAS, 450, 2739
Miller J. M., et al., 2020, ApJ, 904, 49
Moretti M. I., et al., 2018, MNRAS, 477, 2664
Pashchenko I. N., et al., 2018, MNRAS, 475, 2326
Pilipenko S. V., et al., 2018, MNRAS, 474, 3523
Predehl P., et al., 2016, in Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray. p. 99051K, doi:10.1117/12.2235092
Rosen S. R., et al., 2016, A&A, 590, A1
Salvetti D., et al., 2017, MNRAS, 470, 466
Savolainen T., et al., 2021, p. arXiv:2111.04481
Saxton R. D., et al., 2008, A&A, 480, 611
Scaringi S., et al., 2012a, MNRAS, 421, 2854
Scaringi S., et al., 2012b, MNRAS, 427, 3396
Scaringi S., et al., 2015, Science Advances, 1, e1500686
Schinzel F. K., et al., 2017, ApJ, 838, 139
Slane P., et al., 2015, Space Sci. Rev., 188, 187
Sokolovsky K. V., et al., 2018, A&C, 22, 28
Sokolovsky K. V., et al., 2011, A&A, 532, A38
Sokolovsky K. V., et al., 2014, A&A, 565, A26
Sokolovsky K. V., et al., 2017a, p. arXiv:1712.04672
Sokolovsky K. V., et al., 2017b, MNRAS, 464, 274
Sokolovsky K. V., et al., 2020, MNRAS, 497, 2569
Sokolovsky K. V., et al., 2021, p. arXiv:2108.03241
Steinberg E., et al., 2018, MNRAS, 479, 687
Strader J., et al., 2014, ApJ, 788, L27
Vlasov A., et al., 2016, MNRAS, 463, 394
Vurm I., et al., 2018, ApJ, 852, 62

[I] `https://scan.sai.msu.ru/lk/`
[II] `https://github.com/kirxkirx/patpc`