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High-cadence observations of galactic nuclei by the future two-band UV-photometry mission *QUVIK*

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(on behalf of *QUVIK* Science Team)

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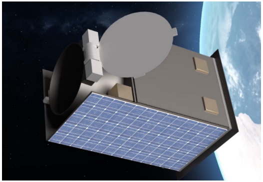
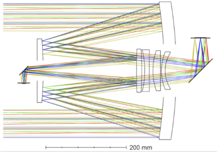
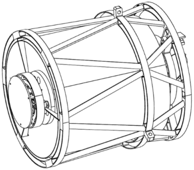
QUVIK – Quick Ultra-VIolet Kilonova surveyor

- **QUVIK** was approved for funding by the Czech Ministry of Transport and the European Space Agency as an ambitious Czech national space mission
- **primary objective:** **kilonovae** following the mergers of neutron stars
- **secondary objectives:** hot stars, supernovae, star clusters, γ-ray bursts, and **(active) galactic nuclei**
- modified Cassegrain of $\sim$ 33 cm; FOV$\sim 1^\circ \times 1^\circ$, PSF$\lesssim 2.5''$
- two bands: NUV (260 - 360 nm) and FUV (140 - 190 nm)







QUVIK – Quick Ultra-VIolet Kilonova surveyor

- scientific targets and program elaborated in three review papers published in the **Space Science Reviews** special issue on *QUVIK*
  1. **mission description and stellar transients** (2306.15080),
  2. **observations of stars and stellar systems** (2306.15081),
  3. **active galactic nuclei and nuclear transients** (2306.15082)

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Science with a Small Two-Band UV-Photometry Mission I: Mission Description and Follow-up Observations of Stellar Transients

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Abstract
This is the first in a collection of three papers introducing the science with an ultra-violet (UV) space telescope on an approximately 130 kg small satellite with a moderately fast re-pointing capability and a real-time alert communication system approved for a Czech national space mission. The mission, called *Quick Ultra-Violet Kilonova surveyor—QUVIK*, will provide key follow-up capabilities to increase the discovery potential of gravitational wave observatories and future wide-field multi-wavelength surveys. The primary objective of the mission is the measurement of the UV brightness evolution of kilonovae, resulting from mergers of neutron stars, to distinguish between different explosion scenarios. The mission, which is designed to be complementary to the *Ultraviolet Transient Astronomy Satellite—ULTRASAT*, will also provide unique follow-up capabilities for other transients both in the near- and far-UV bands. Between the observations of transients, the satellite will target other objects described in this collection of papers, which demonstrates that a small and relatively affordable dedicated UV-space telescope can be transformative for many fields of astrophysics.

Keywords UV space observatory · Kilonovae · Gamma-ray bursts · Supernovae

1 Introduction

The first simultaneous detection of gravitational waves and electromagnetic radiation on 2017 August 17 (Abbott et al. 2017b,a), resulting from a coalescence of neutron stars, marked the onset of multi-messenger astrophysics involving gravitational waves. This exciting observation showed that neutron star mergers are of major importance for enriching the Universe with rare heavy elements such as gold and platinum. The radioactive decay of these heavy elements powers a thermal transient at ultra-violet/visible/infrared wavelengths

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Science with a Small Two-Band UV-Photometry Mission II: Observations of Stars and Stellar Systems

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Abstract
We outline the impact of a small two-band UV-photometry satellite mission on the field of stellar physics, magnetospheres of stars, binaries, stellar clusters, interstellar matter, and exoplanets. On specific examples of different types of stars and stellar systems, we discuss particular requirements for such a satellite mission in terms of specific mission parameters such as bandpass, precision, cadence, and mission duration. We show that such a mission may provide crucial data not only for hot stars that emit most of their light in UV, but also for cool stars, where UV traces their activity. This is important, for instance, for exoplanetary studies, because the level of stellar activity influences habitability. While the main asset of the two-band UV mission rests in time-domain astronomy, an example of open clusters proves that such a mission would be important also for the study of stellar populations. Properties of the interstellar dust are best explored when combining optical and IR information with observations in UV.

It is well known that dust absorbs UV radiation efficiently. Consequently, we outline how such a UV mission can be used to detect eclipses of sufficiently hot stars by various dusty objects and study disks, rings, clouds, disintegrating exoplanets or exoasteroids. Furthermore, UV radiation can be used to study the cooling of neutron stars providing information about the extreme states of matter in the interiors of neutron stars and used for mapping heated spots on their surfaces.

Keywords Techniques: photometric · Ultraviolet: stars · Stars: variables: general · Binaries: general · Open clusters and associations: general · Planetary systems

1 Introduction

The new discoveries in astrophysics during the last few decades were frequently connected with the opening of new observational windows into invisible parts of the spectrum. Recently, the advent of observatories working outside the electromagnetic domain founded a

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Science with a Small Two-Band UV-Photometry Mission III: Active Galactic Nuclei and Nuclear Transients

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Abstract
In this review, the third one in the series focused on a small two-band UV-photometry mission, we assess possibilities for a small UV two-band photometry mission in studying accreting supermassive black holes (SMBHs; mass range $\sim 10^6$–$10^{10}\,M_\odot$). We focus on the following observational concepts: (i) dedicated monitoring of selected type-I Active Galactic Nuclei (AGN) in order to measure the time delay between the far-UV, the near-UV, and other wavebands (X-ray and optical), (ii) nuclear transients including (partial) tidal disruption events and repetitive nuclear transients, and (iii) the study of peculiar sources, such as changing-look AGN, hollows and gaps in accretion disks, low-luminosity AGN, and candidates for Intermediate-Mass Black Holes (IMBHs; mass range $\sim 10^2$–$10^5\,M_\odot$) in galactic nuclei. The importance of a small UV mission for the observing program (i) is to provide intense, high-cadence monitoring of selected sources, which will be beneficial for, e.g. reverberation-mapping of accretion disks and subsequently confronting accretion-disk models with observations. For program (ii), a relatively small UV space telescope is versatile enough to start monitoring a transient event within $\lesssim 20$ minutes after receiving the trigger; such a moderately fast repointing capability will be highly beneficial. Peculiar sources within the program (iii) will be of interest to a wider community and will create an environment for competitive observing proposals. For tidal disruption events (TDEs), high-cadence UV monitoring is crucial for distinguishing among different scenarios for the origin of the UV emission. The small two-band UV space telescope will also provide information about the near- and far-UV continuum variability for rare transients, such as repetitive partial TDEs and jetted TDEs. We also discuss the possibilities to study and analyze sources with non-standard accretion flows, such as AGN with gappy disks, low-luminosity active galactic nuclei with intermittent accretion, and SMBH binaries potentially involving intermediate-mass black holes.

Keywords Galactic nuclei · Accretion flows · Tidal disruption events · Transients · Photometry · Time series

1 Introduction

The growth of supermassive black holes (hereafter SMBHs) residing in the centres of galaxies is a crucial topic in modern astrophysics (Di Matteo 2019). SMBHs can grow by accre-

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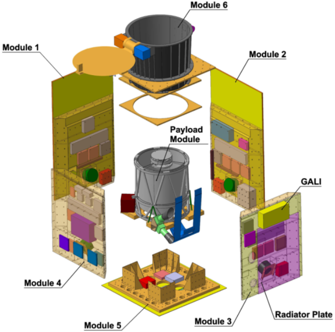
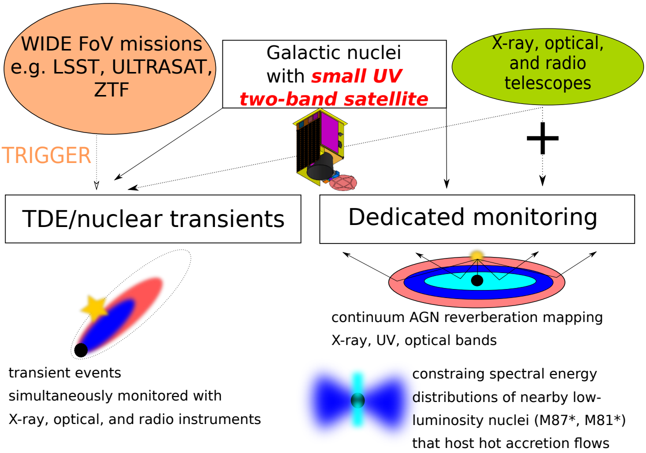
For technical details concerning the *QUVIK* NUV and FUV cameras, see the **poster "NUV and FUV cameras for the Quick Ultra-VIolet Kilonova Surveyor (QUVIK)"** by **Aaron Tohuvavohu** (University of Toronto)



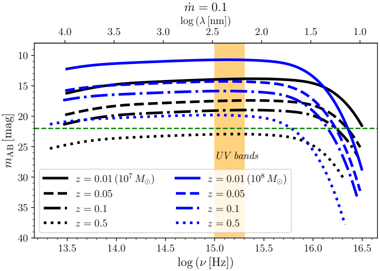
QUVIK Galactic nuclei program

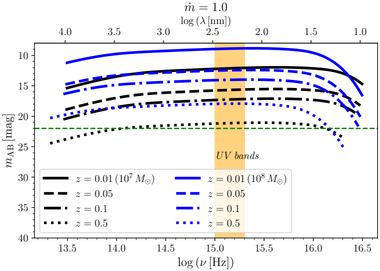
- **monitoring of selected *AGN***: photometric reverberation mapping
- **nuclear transients:** tidal disruption events - TDEs, changing-look AGN, and peculiar sources



QUVIK Galactic nuclei program

- accretion disk UV emission (type I AGN) is observable up to $z \sim 0.5$
- depends on the SMBH mass ($10^7 - 10^8\ M_\odot$) and the relative accretion rate ($0.1 - 1.0$)

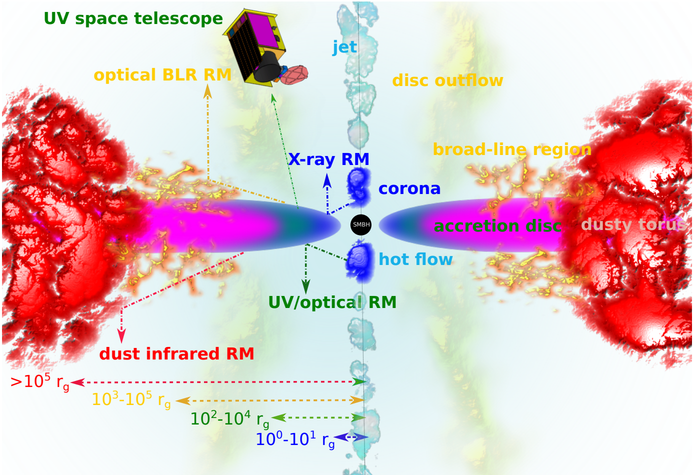




Redshift limit	Limiting u magnitude	Number of SDSS quasars	$t_{\rm int}$ [s], $S/N = 100$
0.5	17.0	151	100.0
0.5	18.0	964	251.2
0.7	17.0	167	100.0
0.7	18.0	1047	251.2

Dedicated monitoring

- **Spatial resolution ⇔ Temporal resolution**
- Different wavelengths probe different scales of an accretion disk and its immediate surroundings



Dedicated monitoring

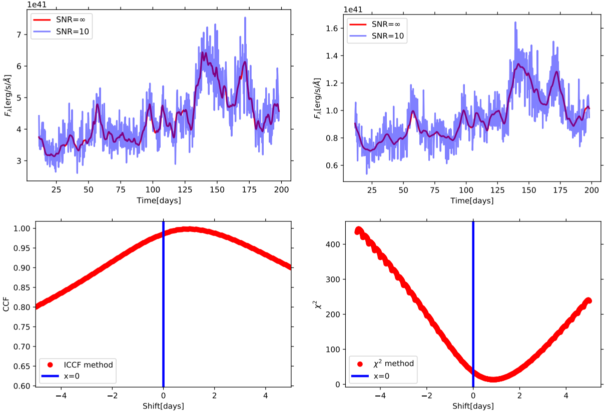
- driving ionizing radiation ΔF_i (X-ray corona)
- reprocessed radiation in the far-UV, near-UV, optical domains ΔF_r
- $$\Delta F_{\rm r}(t) = \int_0^{\tau_{\rm max}} \psi(\tau)\Delta F_{\rm i}(t-\tau){\rm d}\tau\,,$$

  where $\tau = r/c$ is the mean time-delay due to light-travel time, $\psi(\tau)$ is the transfer function of the accretion disk (delay and blurring)

Reverberation mapping		Light-crossing time [days]		
Wavelength domain	Spatial length scale $[r_{\rm g}]$	**10^7 M$_\odot$**	**10^8 M$_\odot$**	**10^9 M$_\odot$**
X-ray	$1-10$	$5.7 \times 10^{-4}-5.7 \times 10^{-3}$	$5.7 \times 10^{-3}-5.7 \times 10^{-2}$	$5.7 \times 10^{-2}-0.57$
UV/optical (*QUVIK*)	10^2-10^4	$5.7 \times 10^{-2}-5.7$	$0.57-57$	$5.7-570$
optical BLR	10^3-10^5	$0.57-57$	$5.7-570$	$57-5700$
optical/infrared dusty torus	$> 10^5$	> 57	> 570	> 5700

Dedicated monitoring

- mock observation with different cadences and SMBH masses of $10^7\,M_\odot$ and $10^8\,M_\odot$
- light curve of the X-ray corona calculated using the Timmer-König algorithm



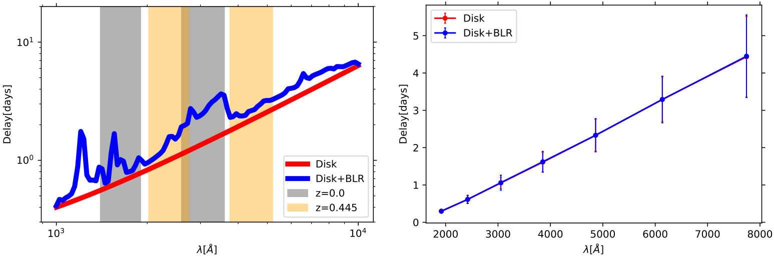
Dedicated monitoring

- for $M_\bullet = 10^7\,M_\odot$, 10-day monitoring with a high cadence of 0.1 days is sufficient
- for $M_\bullet = 10^8\,M_\odot$, cadence can be lower ($\sim 1$ day), but the observation should last for about half a year

$M_\bullet$ ($M_\odot$)	S/N	RMS (%)	ΔT (days)	T (days)	$\tau_{\rm ICCF}$ (days)	$\Delta\tau_{\rm ICCF}$ (days)	τ_{χ^2} (days)	$\Delta\tau_{\chi^2}$ (days)	τ_ψ (days)
10^7	∞	11.40	0.1	10	0.172	0.086	0.135	0.047	0.205
10^7	100	11.50	0.1	10	0.165	0.069	0.125	0.072	0.205
10^8	∞	3.15	0.25	186	1.021	0.182	0.686	0.056	0.786
10^8	100	3.51	0.25	186	0.966	0.193	0.621	0.001	0.786
10^8	∞	3.15	0.5	186	1.028	0.183	0.708	0.047	0.786
10^8	100	3.33	0.5	186	1.017	0.278	1.112	0.250	0.786
10^8	∞	3.15	1.0	186	1.087	0.218	0.698	0.045	0.786
10^8	100	3.32	1.0	186	1.065	0.319	0.527	0.049	0.786

Dedicated monitoring

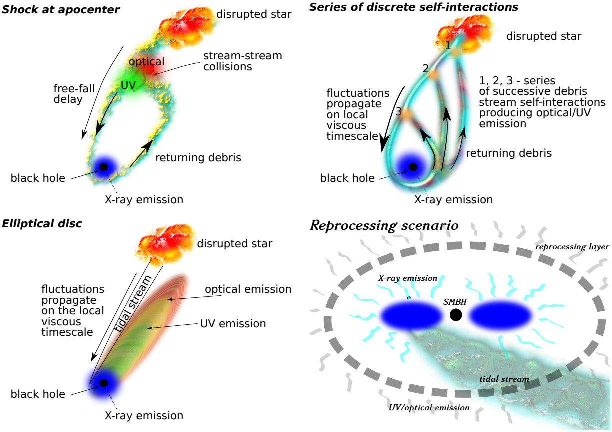
- potential effect of extended media (UFO, BLR) – prolongation with respect to the time delay due to disk reprocessing, $\tau(\lambda) \propto \lambda^{4/3}$
- redshift-dependent, needs further numerical assessment



- calculations based on the **Disk+BLR transfer function** (left) and obtained numerically using **stochastic variability** (right)

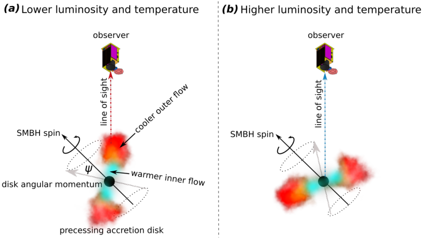
TDE/nuclear transients

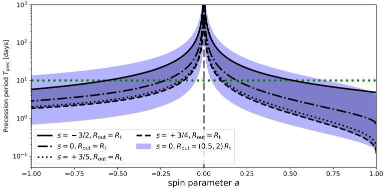
- tidal disruption events are accompanied by bright optical/UV emission that decreases as a power-law ($\dot{M}_{\rm fallback} \propto t^{-5/3}$)
- **unclear origin of the UV emission:** shock-produced or accretion-disk emission?



TDE/nuclear transients

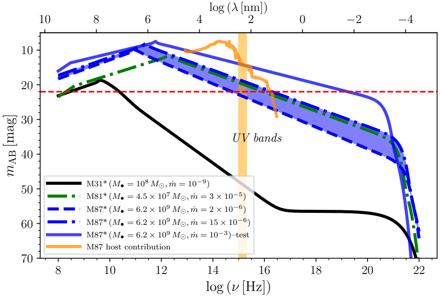
- high-cadence monitoring shortly after the optical/UV outburst could reveal **quasiperiodic modulations due to the Lense-Thirring precession ⇒ constraining SMBH spin**
- for a given periodicity, spin constraints depend on the post-TDE disk parameters (density slope, outer radius) and the SMBH mass





Non-standard accretion flows: low-luminosity AGN

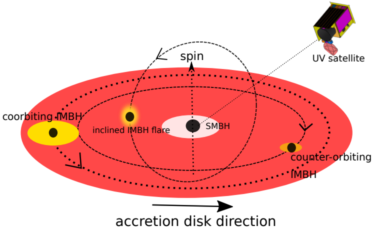
- constraining SEDs of nearby low-luminosity AGN ($10^{-3} \lesssim \dot{m} \lesssim 10^{-2}$)
- contribution of starlight is more relevant and eventually may prevent detecting a fainter AGN

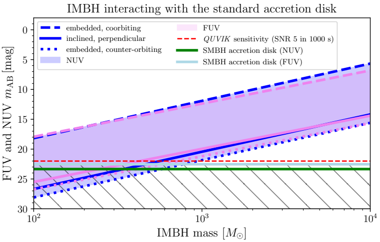


M81 is a nearby (12 Mly) grand spiral with a small jet: suitable source for the disentangling of the host from the core (image credit: HST, GALEX, Spitzer)

Non-standard accretion flows: perturbation by an orbiting IMBH

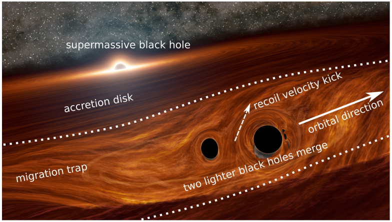
- for an AGN disk, an orbiting IMBH ($m_{\rm IMBH} \gtrsim 10^3\,M_\odot$) that passes through the disk can produce **quasiperiodic UV flashes** (see also Linial & Metzger 2024 for the analysis of UV Quasiperiodic Erupters - QPEs)
- function of an IMBH mass and its inclination





Summary

- **reverberation mapping** of the accretion disk between FUV and NUV bands (and other wavebands)
- origin of the **TDE *UV emission***
- **non-standard accretion**: low-luminosity AGN, changing-look AGN, binary supermassive black holes (“gappy” disks)
- **unexpected discoveries**, e.g. quasiperiodic transients with UV flashes due to an orbiting and inclined intermediate-mass black hole / UV Quasiperiodic Erupters



Credit: R. Hurt (Caltech/IPAC)

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