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Extragalactic panel
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GROND Multiwavelength SEDs of Swift/BAT-selected BASS AGN in Major Galaxy Mergers

Abstract

Establishing and physically understanding the connection between major galaxy mergers and the triggering of vigorous supermassive Black Hole growth is critical for our understanding of galaxy evolution. The Swift/BAT Spectroscopic Survey (BASS) in the ultra-hard (14- 195 keV) X- ray band has been paramount in obtaining a nearly unbiased sample of 1,000+ moderate-luminosity AGN in the local Universe. Here, we propose to use GROND to characterize and obtain the optical to near-IR spectral energy distributions (SEDs) for ∼50 BASS AGN which according to existing DSS imaging are associated with major galaxy mergers. With these data we will be able to confirm the merger nature of the systems, study their physical properties such as stellar mass, ages, etc. and significantly increase the sample of dual AGN in the southern hemisphere. This will also serve as training set and testing for AI-based merger search algorithms that will be applied to future imaging surveys such as LSST.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
GROND/MPG 2.2-m	3 nights	1 nights	Any Any	Any Any

CoIs

Name	Institution	e-mail	Observer?
Tim Hewlett	PUC	thewlett@astro.puc.cl	True
Franz Bauer	PUC	fbauer@astro.puc.cl	False
Claudio Ricci	UDP	claudio.ricci@mail.udp.cl	False
Federica Ricci	PUC	fricci@astro.puc.cl	False
Fabio Vito	PUC	fabio.vito@uc.cl	False
Michael Koss	OnCL	mike.koss@eurekasci.com	False
Giacomo Venturi	PUC	gventuri@astro.puc.cl	False

Status of the project

- Past nights: 3
- Future nights: 0
- Long term: False
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
SWIFTJ0114.4-5522	1:14:24.939	-55:23:49.37	V=14.23
SWIFTJ0123.9-5846	1:23:45.773	-58:48:20.79	V=15.06
SWIFTJ0128.5-5647	1:28:20.497	-56:49:39.59	V=16.23
SWIFTJ0128.9-6039	1:29:7.647	-60:38:42.13	V=17.17
SWIFTJ0130.0-4218	1:29:51.176	-42:19:35.23	V=16.28
SWIFTJ0226.4-2821	2:26:25.717	-28:20:58.85	V=16.19
SWIFTJ0238.2-5213	2:38:19.717	-52:11:32.31	V=15.39
SWIFTJ0345.2-3935	3:45:12.528	-39:34:29.30	V=15.22
SWIFTJ0350.1-5019	3:50:22.988	-50:18:9.41	V=15.28
SWIFTJ0357.5-6255	3:56:19.965	-62:51:39.20	V=17.56
SWIFTJ0422.7-5611	4:22:24.062	-56:13:32.28	V=15.82
SWIFTJ0534.8-6026	5:34:30.898	-60:16:15.52	V=17.07
SWIFTJ0557.9-3822	5:58:2.055	-38:20:4.43	V=14.34

SCIENTIFIC AIM AND RATIONALE

The formation and growth of supermassive black holes (SMBHs) remains one of the most important problems in modern astronomy. Simulations (e.g. Di Matteo et al. 2005, Hopkins et al. 2006, 2008) suggest that the turbulent process of a major galaxy merger can power the activation of an intense Active Galactic Nucleus (AGN). In the process of merging, as two galaxies spiral around each other, violent shocks disrupt the structure of the galaxies enabling gas to fall onto the SMBH triggering the AGN (e.g., Barnes et al. 1991). Observationally, while originally controversial, it is now well established that major galaxy mergers trigger the most intense and often heavily obscured SMBH growth episodes (e.g., Koss et al. 2010, Treister et al. 2012, Glikman et al. 2015, Ricci et al. 2017, Donley et al. 2018). As a consequence, while only a relatively small fraction, ∼10%, of the AGN can be associated with major galaxy mergers, they are responsible for the most violent nuclear accretion events and can account for ∼60% of the total SMBH growth (Treister et al. 2012). **Therefore, it is in major galaxy mergers that we expect the strong observational connection between SMBH growth and galaxy evolution to be established.**

During the process of merging, close dual AGN (i.e., two AGN in a merging system separated by <10 kpc), with two actively growing SMBHs hosted by a pair of merging galaxies, are predicted (Van Wassenhove et al. 2012, Blecha et al. 2013). As extreme cases of the merger-driven AGN model, the detection and frequency of dual AGN on kpc scales provide constraints on models of galaxy formation and black hole growth. Understanding the types of galaxies and specific merger stages where dual AGN occur provides important clues about the connection between SMBH growth and galaxy mergers. Dual AGN are also the seed population for pc-scale binary AGN, which while are difficult to detect observationally will become extremely important once the next generation of space-based gravitational waves detectors such as *LISA* start operations. At low redshifts, our group has directly demonstrated the high incidence of occurrence of both major galaxy mergers and dual AGN in moderate luminosity AGN (Koss et al. 2012, 2018; Figure 1).

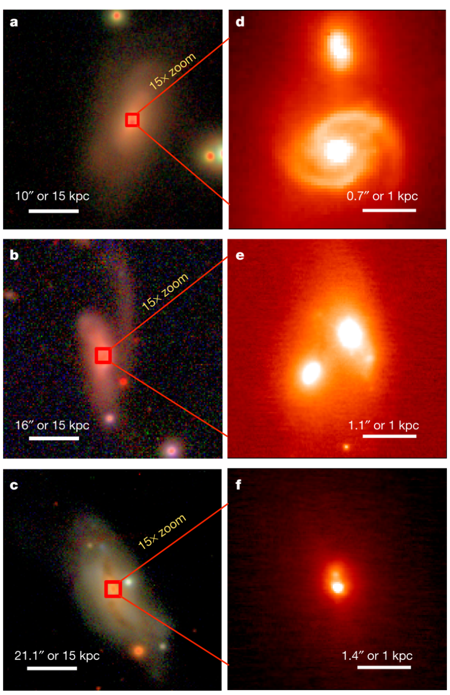

Figure 1: Examples of AGN in previously-missed hidden galaxy mergers selected from the Swift/BAT BASS survey, as reported by Koss et al. (2018). Panels a-c show existing SDSS imaging in the *gri* bands at worse spatial resolutions and shallower than those proposed here, while the panels d-f show AO-assisted K band images obtained using the NIRC2 camera at Keck. These results further emphasize the need for deep multi-band imaging, as proposed here, in order to properly quantify the importance of major galaxy mergers for AGN triggering and to guide their automatic identification in future surveys such as LSST.

The *Swift* BAT Spectroscopic survey (BASS) in the ultra-hard X-rays provides a largely unbiased sample of ∼1,000 mostly local ($<z>= 0.05$) moderate-luminosity AGN ($\log L_{2-10keV}\simeq 43$; Koss et al. 2017, Oh et al. 2018). This sample is ideally suited for the study of AGN triggering and its connection to major galaxy mergers for several reasons: *i*) Selection in the ultra-hard X-rays by Swift BAT is relatively unaffected by host galaxy properties and Compton-thin obscuration, which can strongly affect IR and optical line and color selection. *ii*) Archival X-ray observations from *XMM-Newton*, *Chandra*, or the *Swift* XRT exist for 99.8% of the sample. *iii*) Ultra-hard X-rays are a reliable and direct tracer of the bolometric luminosity of AGN, as this band it is not affected by host galaxy contamination or by obscuration. *iv*) The BAT-detected AGN are similar in bolometric luminosity to moderate-luminosity AGN at higher redshifts ($z\sim 0.7$, near the peak of black hole growth) where dual AGN studies suffer from insufficient resolution. Furthermore, the Swift/BAT observations nicely complement our ongoing study of the multiwavelength properties of the *NuSTAR* serendipitous sources (e.g., Lansbury et al. 2017), which trace similar luminosity AGN at significantly higher redshifts.

We propose here to use GROND at the MPG/2.2m in order to construct optical to near-IR spectral energy distributions (SEDs) for ∼50 nearby AGN selected from ultra-hard X-ray *Swift* BAT observations in the southern hemisphere,

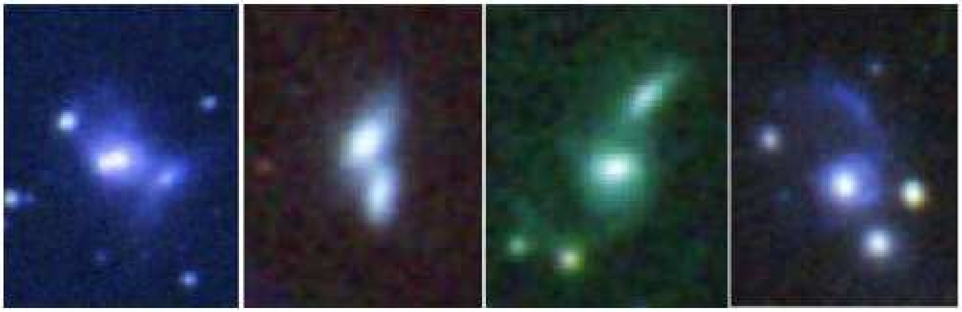

Figure 2: Example DSS images of four of the proposed BAT AGN targets in this survey. The low resolution of the DSS makes it difficult to detect secondary nuclei, and low surface brightness tidal tails and bridges (critical to determining the merger stage) are often too faint to be discerned. Important quantities such as host galaxy color and stellar mass also cannot be reliably determined in complicated merging systems using DSS two-color imaging and critically require the proposed multi-band optical to near-IR GROND observations.

which according to our visual classification of shallow DSS imaging appear to be undergoing a major galaxy merger (Fig. 2). The sample was drawn from the *Swift* BAT 105 month catalog (Oh et al. 2018). All 1632 hard X-ray sources were visually inspected and classified morphologically. From this process, we obtained a sample of $\sim$200 major merger candidates, of which we propose to follow up those reachable from the southern hemisphere. Once these candidates are confirmed with deeper multi-band imaging, this will be the largest sample of major galaxy mergers hosting at least one AGN to date. GROND is ideally suited for this project, as it provides simultaneous coverage in 7 photometric bands from g' to K. GROND is unique for these purposes: there is no other instrument available to us elsewhere that can provide an optical to near-IR spatially-resolved SED on a single exposure. The main scientific goals of our project are:
(a) With the proposed observations we will **identify robust galaxy merger candidates** and potential dual AGN by constructing spatially-resolved optical and near-IR SEDs, which will be then followed-up by optical and near-IR IFU observations using the ESO/VLT and other 8m-class telescopes and ALMA at sub-mm wavelengths.
(b) Estimate the stellar masses of the host galaxies by performing SED fitting using stellar population templates. The stellar masses will be derived independently for each galaxy participating in the merger and hence will allow us to measure the relative frequency of black hole growth through minor and major mergers that can then be compared to simulations. Furthermore, this will enable to obtain spatially-resolved measurements of the dust obscuration (extinction) and star formation rates from the observed optical/near-IR colors.
(c) Understand SMBH growth in the merging sequence that can be used as a template for high redshift AGN at moderate luminosities, as those traced by the deeper but narrower *NuSTAR* extragalactic surveys (Harrison et al. 2015, Lansbury et al. 2017). We will further use the FERENGI code (Barden et al. 2008), in order to understand selection effects which are critically important in order to interpret current results obtained by the Hubble Space Telescope and future *JWST* observations of high redshift mergers/dual AGN candidates.
(d) The proposed observations will be further used as input for training and testing of Artificial Intelligence algorithms aimed to automatically identify major galaxy mergers up to high redshifts in large optical and near-IR imaging surveys such as *LSST*. Taking advantage of the multi-band imaging offered by GROND, we will be able to directly mimic the effects of band-shifting due to redshift, while the FERENGI code will be used for the surface brightness dimming. This will be the base of the work of co-I Dr. Tim Hewlett, postdoctoral fellow at the Institute of Astrophysics, PUC.

Multi-band broad SEDs, such as those proposed here, will allow us to separate the AGN and host galaxy components using for example the templates of Assef et al. (2010). Once this decomposition is done, it will be possible to derive physical properties of the stellar populations in the host galaxy of the hard X-ray emitter, such as stellar masses, luminosity-weighted ages, and metallicities. This will be done by fitting the photometry obtained in 7 bands from the optical to the near-IR provided by the proposed GROND observations using for example CIGALE (Code Investigating GALaxy Emission[1]; Noll et al. 2009) as it was done in the past by e.g., Ciesla et al. (2015). While good spatial resolution is important, it is not critical for our project. Given that these are all low redshift, $z\sim$0.03-0.08, systems, they are expected to be well resolved spatially on seeing-limited observations, as can be seen in Figure 2. Hence, it is not necessary for this project to use Adaptive Optics (AO) observations, that are more expensive in telescope time given the large overheads. Furthermore, for most sources in our sample there is no natural guide star available in the field, critical to perform the tip-tilt correction, and hence AO observations are not feasible.

The physical information for these AGN host galaxies is critical in order to study the proposed connection between SMBH growth and galaxy evolution and to compare with the properties of the sources in the *Swift* BAT and *NuSTAR* survey fields. For example, we could test whether the age of the most recent significant stellar population correlates with

[1] `https://cigale.lam.fr/`

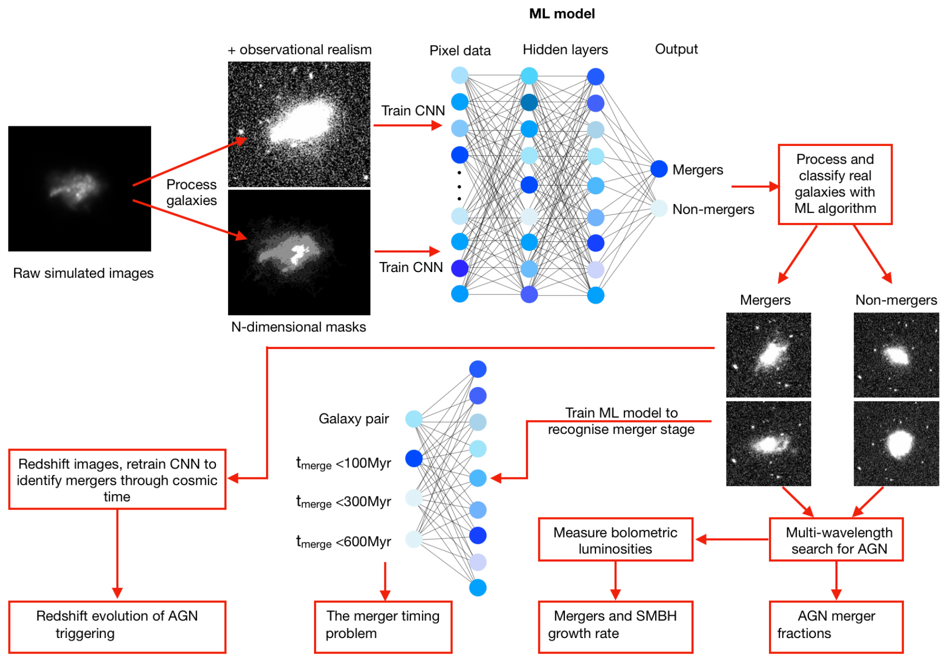

Figure 3: Schematic description of the AI framework used to efficiently detect major galaxy mergers in large imaging surveys such as LSST. The proposed GROND observations will be used to obtain a statistically significant training set and testing sample for this algorithm, based on real major galaxy mergers hosting 1+ growing SMBHs. This will be further complemented with simulated galaxies from large-scale cosmological simulations.

AGN luminosity, or amount of obscuration, or compare the stellar masses and other properties of AGN host galaxies with inactive galaxies. For sources with bright unobscured AGN, the optical AGN emission will be extracted using GALFIT (Peng et al. 2002), a 2D modeling program that fits the galaxy and AGN light profile to spatially separate the AGN from the galaxy (e.g. Koss et al. 2011). While it can be expected that the nuclear regions can be subject to significant obscuration, average galaxy properties would be derived without major biases. The near-IR photometry provided by GROND will also certainly help to reduce the effects of obscuration.

Identifying major galaxy mergers hosting one or more AGN in an unbiased X-ray survey is also critical for training and testing of Artificial Intelligence (AI) algorithms that will then automatically identify them in large imaging surveys such as LSST. As can be seen in Figure 3, we will use the derived sample of major galaxy mergers, which will span a wide range of properties such as merger stage, mass ratio, etc., to train and extensively test these algorithms. Specifically for our work, we will mix both simulated and real galaxies for this training and hence a large sample of the latter is required. Then, we will test these algorithms on the GROND sample to iteratively improve them and establish their efficiency under a variety of conditions. Then, we aim to be able to use them to identify galaxy mergers in large imaging surveys. Early experiments show that these AI-based algorithms can identify up to $\sim$60% of the total galaxy mergers, in comparison to other automatic methods based on structural parameters or even visual classifications, that can only reach $\sim$30% efficiency. This is then critical to understand the connection between SMBH growth and galaxy mergers. This is the main goal of the research of Dr. Tim Hewlett, postdoctoral fellow at PUC.

The proposed GROND observations of $\sim$50 *Swift* BAT sources selected as major galaxy merger candidates, will allow us to at least double the number of candidate dual AGN reachable by southern telescopes. This will then allow us to increase the diversity of merger types, host galaxies, Eddington ratios, separations to best understand the merger driven black hole growth. This will be done by producing the individual optical to near-IR SED for each nucleus, which will be used to search for AGN signatures in the continuum.

References

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CURRENT STATUS OF THE PROJECT

This proposal is the natural continuation of the current work of our research group and fits very well in the context of several projects that we are currently carrying out together with our international collaborators, with a strong Chilean participation.

The BAT AGN Spectroscopic Survey (BASS) project is an ongoing project aiming to study the growth of nearby super massive black holes by combining an ultra-hard X-ray (14-195 keV) selected AGN with optical and near-IR imaging and spectroscopy. The BASS project already acquired optical spectroscopy for 1000+ sources out of these ultra-hard X-ray selected Swift/BAT sources from various surveys (SDSS, 6dF) and ground-based telescopes (Kitt Peak, Gemini North, Gemini South, SAAO). The project already produced 12 publications, with many more submitted and in preparation. Among the most important papers we can highlight the first releases of the optical (Koss et al. 2017, ApJ, 850, 74) and X-ray (Ricci et al., 2017, ApJS, 233, 17) catalogues, a critical re-examination of the famous Γ_X-L/L_{EDD} correlation (Trakhtenbrot et al., 2017, MNRAS, 470, 800), a high impact publication reporting that most of the AGN obscuration is nuclear and dominated by the radiation pressure from the central engine (Ricci et al., 2017, Nature, 549, 488) and the report of the discovery of a significant number of merger-triggered AGN in nearby late-stage systems (Koss et al., 2018, Nature, 563, 214).

In addition, and as described in the scientific justification, the confirmation of the presence of a major galaxy merger for a significant fraction of the sources in the *Swift* BAT sample, as proposed here, will enable to carry out extensive follow-up studies. Particularly important in this regard is the MODA survey that we are currently leading at PUC. This project aims to study the multiwavelength properties of dual AGN at z<1. Currently, we have obtained VLT/MUSE, SINFONI and VISIR and ALMA observations for 5 of these dual AGN visible from the southern hemisphere. The first results on the archetypical source NGC6240 were already published in a high-impact Nature paper (Muller-Sanchez et al., 2018, Nature, 556, 345), with a more detailed analysis of the VLT/MUSE (Privon et al., in prep.) and high resolution ALMA data (Treister et al., in prep.) currently in preparation. We have already published the results of the combined VLT/MUSE and ALMA observations of the Mrk 463 system (Treister et al., 2018, ApJ, 854, 83), while a similar dataset was obtained and analyzed for the Mrk 739 by PUC current master student Dusan Tubin and will be soon submitted for publication (Tubin, D. et al., in prep.). We expect that the proposed GROND observations will allow us to more than double (from 8 to $\sim$20) the number of confirmed dual AGN at z<0.1 visible from the southern hemisphere, which is critical to achieve our scientific goals given the very low number of sources in our sample.

The proposed observations were already approved in period 2017A, as part of program CN2017A-125. The observations were scheduled for May 22-25, 2017 and completely lost due to a combination of rain, snow and high winds. We did not however submitted again this proposal because we wanted to first focus on other projects and more importantly because we wanted to make sure that we had adequate person power to dedicate to this project. Now postdoctoral researcher Dr. Tim Hewlett has joined our AGN research group at the Institute of Astrophysics of the Pontificia Universidad Catolica and will actively work on this project. In addition, our group has now significantly increased its number of students at both the undergraduate and graduate levels and so we are confident that we can quickly reduce, analyze and publish the requested data, which we expect will constitute the core of the thesis work of a graduate student at PUC supervised by the senior members of this project.

TECHNICAL DESCRIPTION

Our main goal is to use GROND at the MPG 2.2m telescope to obtain optical to near-IR photometry in 7 broad bands for the *Swift* BAT ultra-hard X-ray sources in the Southern hemisphere which according to the existing low quality DSS imaging appear to be undergoing a major galaxy merger, as shown in Figure 2. Considering only those sources visible this semester we assembled a sample of 51 systems.

Unfortunately GROND does not have an exposure time calculator. However, very useful guidelines are provided by the instrument team and available at `http://www.mpe.mpg.de/~jcg/GROND/operations.html`. We use this information to compute the required exposure times to achieve our scientific goals. The sources in our sample range from V=16 to $V\simeq$18. All magnitudes on the proposal's target list are given on the V band. Since we aim to detect low surface brightness features such as tidal tails, which are clear signs of ongoing major mergers, we aim to reach a SNR >50 for the total magnitude of the system. Based then on the sensitivity tables provided by the GROND team described above we estimate that reaching the neccesary depths for average La Silla seeing conditions, $\sim1''$, will require a total of $\sim$20 minutes of observing time per source on average. Since the observations will be carried out in visitor mode, we will adapt the exposure times in real time in order to reach appropriate surface brightness limits, adapting for the specific observing conditions and magnitude and surface brightness distribution of each system.

Observational overheads are unfortunately not publicly available for this instrument. In order to obtain this information, we had long conversations and discussions with the MPG2.2m observers such as Dr. Sam Kim, which are luckily hosted at the Astro-engineering center at PUC. Adding telescope offset, CCD readout and other overheads we estimate a total required time of $\sim$0.5 hours per source. Considering calibrations, standard stars, etc., we estimate that we require a total of 3 nights (26 hours+calibrations) this semester in order to observe all our candidates.

If needed, in order to get this project started, we can take advantage of a single night if required by the scheduling constraints. Given that the bulk of our observations focus on the optical bands from blue to red wavelengths, we prefer gray nights, but if needed we can perform our observations on bright time. Sources are roughly evenly spread in RA and therefore we are ready to observe on any available night this semester.