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Exploring Radio and Jet Properties Across the Black Hole Mass Scale

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Summary

In this thesis we studied the multi-wavelength spectra of accreting black holes (BH)s across the mass and luminosity scales, focussing particularly on an age-old mystery: *"Why are some of these accreting sources radio loud, and others not?"*

Although this question is particularly valid for the supermassive BHs (SMBH)s in active galactic nuclei (AGN), the issue stands across the entire observed 8 magnitude BH mass range. Driven to gain better understanding of this problem we approached it from multiple angles, starting out by studying the broadband spectra of individual sources in the first half of the thesis, thereby growing our understanding of the jet-phenomenon and the conditions in which jets may be observed.

In doing so we work our way up to the study of large, un-biased samples in the latter half of the thesis. For these big samples, the key is to minimise biases contained in them. This proves to be difficult due to inherent biases, as well as difficulty avoiding introducing new biases by applying usual techniques, e.g. by correcting for intrinsic dust attenuation. However, even allowing for these problems our results prove to be interesting and pave the way for future work in the 'Big Data' era with next generation optical surveys and radio telescopes.

Chapter 2

In Chapter 2 we studied the peculiar microquasar GRS 1915+105 that portrays a rather special jet-bearing state. Although generally jets are associated with the low luminosity hard and quiescent X-ray states, this BH is able to sustain its jets at near-Eddington luminosities in its so-called *plateau* state. We use an outflow-dominated model (Markoff et al. 2005; hereafter MNW05) to model 2 quasi-simultaneous broad-band spectral energy distributions (SED)s. Although the MNW05 framework was actually designed for spectral fitting of low-luminosity sources it is able to cope with this high-luminosity source remarkably well, suggesting the plateau state may be GRS 1915+105's version of the canonical hard state, despite the fact that the plateau state occupies a more extreme part of parameter space. An important example of the latter is that the region where the particles in the jet are first accelerated appears to be much farther out in GRS 1915+105. Also the plateau state jet requires an extreme magnetic domination of the equipartition factor that is about two orders of magnitude larger than common in the hard state. It is mainly with these parameters that we run into limitations of the model. The current version can not self-consistently determine the dependencies of e.g. the acceleration front distance on other jet parameters. The equipartition factor also shows a degeneracy with the other energy-budget related parameters (jet power and electron temperature).

Currently a new magneto-hydrodynamic framework is being constructed, based on the work of Polko et al. (2010, 2013, 2014) where-in the dependencies of all relevant energy and geometry related parameters are determined self-consistently from first principles. This work is currently being implemented (Ceccobello et al. in prep.), and this "next-gen" framework will greatly benefit from the pioneering work done in this (and the next) Chapter (as well as previous explorations and continuous refinements of the model described in (e.g. Falcke & Biermann 1995; Falcke 1996; Markoff et al. 2001a, 2003; Gallo et al. 2007; Migliari et al. 2007; Markoff et al. 2007, 2008; Maitra et al. 2009b,a, 2011; Plotkin et al. 2015; Prieto et al. 2016; Connors et al. 2016), that lay the ground work for this model, by discovering possible trends and exploring the relevant parameter space.

As suggested by its duty cycle (Deegan et al. 2009), GRS 1915+105 should return into quiescence somewhere this century. Such an event would be an excellent testing ground for these frameworks and further understanding of accretion theory at low and high Eddington luminosity.

Chapter 3

The third Chapter focusses on a source that in terms of the mass and luminosity scales is diametrically opposed to the source in the second Chapter. The low-ionisation nuclear emission region (LINER) in M94 is a low-accretion rate supermassive source. Although this is not the first LINER studied within the MNW05 framework, it is the closest type-2 LINER to Earth and therefore we have a relatively good view of this source, despite its low luminosity. This is compounded by the fact that we view this galaxy disk-on, meaning we get a relatively clean view of the nucleus. We compiled a high resolution nuclear broadband SED, starting in radio with the reduction of one of the first datasets obtained by e-MERLIN after a major upgrade from the old MERLIN array. We also managed to obtain previously unpublished data from the Plateau de Bure Interferometer (PdBI) and the Combined Array for Research in Millimeter-wave Astronomy (CARMA; both at submm. wavelengths) and completed the SED with archival *HST* and Chandra data.

We find (contrary to assumptions in Nemmen et al. 2014) that a jet-dominated model can well-approximate the M94 SED. The finding are fully consistent with previous (low luminosity) AGN modelled with MNW05 and show remarkable similarities to stellar mass black hole binaries (BHB)s in quiescence. However we see a similar effect when approximating the M94 SED as we saw when fitting the GRS 1915+105 SED: We find multiple solutions that explain the radiation observed, however we are unable to ascertain whether optically thin synchrotron radiation or synchrotron self-Compton dominates the X-ray spectrum, from modelling and/or statistics alone. Although a more advanced version of a jet-dominated framework (as described above) could solve this, we also have to consider the fact that there is an inherent degeneracy in the synchrotron output of a jet: The power going into the jet scales with the accretion power liberated. This jet power is consequently distributed into both particle and magnetic energy densities. If more power is diverted into the former the effect is a larger number of particles radiating, while if the power going into the magnetic fields is boosted, an equal number of particles will radiate more. Such degeneracies will remain difficult to break.

Chapter 4

In this Chapter we study the relation between average radio and (H β and [O III]) optical emission line luminosities of a sample of (21 425 Balmer uncorrected/ 13 930 Balmer corrected) optically selected AGN. We median-stack 1.4 GHz radio observations from the Very Large Array (VLA) Faint Images of the Radio Sky at Twenty-Centimetres (FIRST) that are counterparts to Sloan Digital Sky Survey (SDSS) optical spectroscopic data and in doing so build an unbiased sample of LINERs, Seyferts and QSOs. Using optical emission line ratios we remove galaxies whose ionisation is dominated by star formation and split the (non-QSO) sources where a central hard continuum source performs this role into two subgroups: the typically higher accretion rate Seyferts and lower accretion rate LINERs. The stacking method greatly lowers the noise floor of the original data by a factor of ~ 20 (depending on the number of sources in a stack). We bootstrap the parameters of interest to assess their statistical quality. We consider the effects of both including and excluding a correction of the optical lines for extinction in the host galaxy (dust attenuation).

We find that LINERs show systematically steeper median radio vs. line luminosity relations than the higher-accretion rate AGN, with power-law indices in the range 1.2–

1.6 (for different mass bins and extinction assumptions), compared to indices for the higher-accretion rate AGN in the range 0.6–1.0. These results are fully consistent with a scenario where LINER jet powers scale linearly with accretion rate $\dot{m}$ (for which simple jet synchrotron models predict a scaling of $L_{\rm rad} \propto \dot{m}^{1.4}$ for flat spectrum jets). In contrast, the Seyferts and QSOs are consistent with sub-linear scaling of jet power with accretion rate, making them substantially more radio-quiet than LINERs at higher luminosities. This split in behaviour clearly links LINERs with the hard state of accreting stellar mass black holes, while Seyferts and QSOs are equivalent to the soft state. Furthermore, the observed radio vs. line luminosity relation for LINERs can be extrapolated to naturally explain the population of high-luminosity radio-loud AGN. The different non-linear scalings of radio luminosity with accretion rate are thus responsible for most of the observed range of AGN radio loudness, rather than differences in some other parameter such as black hole spin.

Chapter 5

In the last chapter we employ a different method to build an unbiased sample. In the previous sample we exploited the most complete currently available sample in radio astronomy: The FIRST survey covers a large footprint of over 10 000 quasi-contiguous square degrees. However in order to keep the total survey observation time within feasible limits the observing frequency and baseline configuration were limited (to 1.4 GHz and B configuration, respectively). For the same array, higher frequencies and larger baselines yield a higher resolution, but would also yield a smaller observing field and hence require an increased amount of time to observe the same footprint. Not only would such higher resolution yield less contamination of nuclear observations by extended emission and emission from a young stellar population from the increased resolving power, but also due to the steep spectrum nature of such non-nuclear processes, increasing the observing frequency can offer double-fold benefits. Hence in this Chapter we focus on working with higher frequency A and B configuration (4.8 GHz) C-band observations.

In a large-scale survey like the VLA FIRST the entire footprint is observed relatively homogeneously. Hence biases can be assumed to be minimal and all available data can generally be used. At higher frequency mainly targeted observations (or small-footprint deep surveys) are available in the VLA archive. Such data may still be useable if observations of sources of interest were performed serendipitously. In this chapter we therefore explore building a sample consisting only of sources that were optically selected using SDSS data and that were serendipitously observed by the VLA at 4.8 GHz. The initial results of cross-correlating the chosen SDSS sample with all the VLA archival C-band observations available are promising: Many hundreds of serendipitously observed SDSS source coordinates are found, sharing amongst them thousands of observations. To reduce these thousands of observations we created an automated pipeline that showed a success rate of $\sim$ 55%. Unfortunately after performing necessary cuts of unreliable data only about $\sim$10% of the original radio data remains. This amount of data is insufficient to perform a median-stacking analysis as in the previous Chapter, so we are limited to do an individual source study, that does not go equally deep (in terms of noise and sensitivity).

The final sample is consistent with previous samples by e.g. Best et al. (2005a); Ho et al. (1995); Nagar et al. (2002b, 2005b); Panessa et al. (2006), however our sample exhibits a wider spread in accretion rate. Due to the method compiling the sample our sample includes objects that are more rare, however, as our sample is serendipitous it is more representative of the true AGN population. In the future we aim to do a full study, interpreting this sample in terms of the results of Chapter 4.

In the near future we may expect to resolve many of the issues encountered in these Chapters. In recent years the VLA has been upgraded to a new configuration dubbed JVLA (similarly to the upgrade of MERLIN into e-MERLIN, from which radio data was used in Chapter 3). If JVLA performs a similar survey as the VLA FIRST used in Chapter 4, with the new technical capabilities, observations of similar depth can be performed in a fraction of the time needed before (Helfand et al. 2015; effectively allowing smaller source numbers and finer mass/accretion rate bins in that Chapter). Furthermore, with new large-footprint observatories entering scientific operation in the years to come, we are about to enter the transient era (Metzger et al. 2015). The observing frequencies of the Square Kilometer Array (SKA, slated to operate by 2020), the Cherenkov Telescope Array and the Large Synoptic Survey Telescope (LSST) are spread over the electromagnetic spectrum and these observatories will be able to do large FOV observations with high cadence, allowing for an unprecedented depth in the combined observations on a relatively short time-scale. A wealth of data for astronomers studying black holes across the mass and luminosity scales using high S/N, high frequency precision, detailed broadband SEDs can thus be expected.