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Faint quasars at very low frequencies

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English Summary

At the time of the discovery of the first quasar, 3C273, the idea that black holes (BHs) exist at the center of the majority of galaxies, and the fact that galaxies are moving away from us, challenged the paradigm of a non-evolving universe that was accepted by contemporary cosmologists and astronomers. Since then, the continuous advances in astronomical instrumentation have allowed us to understand the profound role of BHs in the formation and evolution of galaxies.

More than 50 years since the discovery of 3C273, we now know of more than half a million quasars that are actively accreting matter, both in the local universe and out to an epoch when the universe was less than seven hundred millions of years old. Their intrinsic high luminosity allows us to study in great detail many of the observational signatures of the BHs are their active engines.

This thesis focuses on studying the properties of quasars from a radio-astronomy perspective. Quasars exhibit radio properties that provide important insights about their triggering mechanisms, feedback processes, environments, host galaxies, and evolution. The brightest radio quasars, often referred to as radio-loud quasars (RLQs), are possibly powered by the most massive BHs and are located in the most massive structures in the universe; however the majority of quasars are undetected at radio-wavelengths (radio-quiet quasars, RQQs), and are thought to be powered by less massive BHs.

Quasars

Initially, the first quasar discovered was mistaken for a star with an unusual spectrum, within our own galaxy due to its star-like morphology and high-luminosity. This confusion is still reflected in the name “quasar”, which is an acronym for quasi stellar radio source. The extragalactic nature of quasars was first recognized by Dutch-American

astronomer Maarten Schmidt, who identified the broad emission lines in the spectra as hydrogen emission lines, which were shifted towards the red end of the spectrum by over 15%, confirming them as extragalactic objects. Quasars have a variety of characteristics that make them different from other active galactic nuclei. The presence of strong, broad emission lines is a defining characteristic of quasars, and they are attributed to clouds of hot, dense, highly excited gas moving rapidly, close to the central BH. The mass of the central BH can be estimated, assuming that classical Newtonian mechanics describes the motion of gas around it, and is typically found to be several million solar masses. (or you could express this as $> 10^6 M_{\odot}$). Temporal variability in luminosity is another important characteristic of quasars and one of the first to be studied. For example, the first quasar discovered, 3C273, exhibits variability on periods ranging from days to years. This short-term variability suggests that the emission comes from a compact source with a size no larger than a few light years. The broad emission lines of quasars (especially the Ly_{α} line) make the colors of quasars very different from those of galaxies and most stars. This has motivated a number of major surveys dedicated to search for high- z quasars in the last two decades. As a result, there are more than 592000 quasars currently known, up to $z = 7.5$. The radio continuum observations are also important tools that help to improve our understanding of quasars. Although, the majority of quasars have weak radio emission (RQQs) and usually remain radio-undetected in wide-field shallow radio surveys, around 10 – 15% of the quasars are hundreds to thousands of times brighter in radio maps (RLQs). RLQs often present radio morphologies characterised by bright collimated jets emanating from their nucleus. The reasons why a quasar becomes radio-loud are still a subject of debate and investigation.

Very Low-Frequency Radio Astronomy

The origin of the radio emission in quasars is still not completely understood. In the brightest radio quasars, the radio emission is generated by the conversion of potential energy into electromagnetic energy released as synchrotron radiation and manifesting itself as large-scale structures (radio jets and lobes), while in the fainter radio quasars

star-forming processes taking place in their host galaxies are also thought to be responsible for a fraction of the energy output at radio frequencies. The radio spectrum can be described using a power-law of the form $S_\nu \propto \nu^{-\alpha}$, where S_ν is the source flux, α is the spectral index, and ν is the observing frequency. The spectral index is typically $\alpha \approx -0.70$, therefore, the radio brightness of quasars increases at low-frequencies.

The Low Frequency Array (LOFAR) is a new radio telescope operating at very low-frequencies (10-240 MHz) based on revolutionary phased-array technology. A phased-array radio-telescope is composed of stations that contain a certain number of dipoles at fixed orientation. The signals of the dipoles are combined electronically to simulate a digital dish. This eliminates the need for expensive mechanically operated antennas used in radio-telescopes based on a steerable antenna design such as the Very Large Array (VLA) and Giant Metrewave Radio Telescope (GRMT). LOFAR has two different types of dipole antennas: Low Band Antenna (LBA) and High Band Antenna (HBA), optimized to operate at 10-80 MHz and 120-240 MHz, respectively. The majority of LOFAR stations are located in The Netherlands, with at least 13 stations located in Germany, France, United Kingdom, Ireland, Sweden, and Poland. Even LOFAR operating only with the Dutch stations provides unprecedented sensitivity and angular resolution at low-frequencies, while the addition of international stations increases the angular resolution by a factor of 10. Because the LOFAR beams are digital, it is possible to create different combinations of pointing directions and observing frequencies, limited only by the total bandwidth of the radio-telescope. Thus, the multi-beam capabilities, large instantaneous field-of-view, excellent sensitivity, and high-angular resolution make LOFAR a powerful sky-survey machine.

Pushing towards higher sensitivities and angular resolutions at very low-frequencies brings new challenges. The most difficult of these challenges is the Earth's ionosphere, which can have a large impact on the observations by causing the apparent spatial displacement of stationary radio sources in the images. Therefore, new calibration algorithms that can efficiently account for the ionospheric distortions are required.

This Thesis

In this thesis, the main tools used are low-frequency and high-frequency radio imaging, spectroscopic quasar catalogs, and ancillary optical and infrared data. The second chapter of the thesis uses existing radio and spectroscopic catalogs of quasars to study the clustering properties of RQQs and RLQs. The third chapter uses a directional-dependent calibration algorithm known as facet-calibration to obtain a deep LOFAR 150 MHz mosaic of the NOAO Deep Wide-field Survey (NDWFS) Boötes field. The remaining chapters combine the catalog obtained from the deep LOFAR mosaic presented with ancillary optical/infrared data to study the selection of high- z quasars using LOFAR observations, and to investigate the evolution of radio-selected quasars with redshift.

Chapter 2 investigates the clustering properties of 45441 radio-quiet and 3493 radio-loud quasars in the range $0.3 < z < 2.3$. Our results support a scenario where RLQs inhabit dark matter haloes that are at least one order of magnitude more massive compared with those hosting RQQs. This suggests that there is a real dichotomy between RLQs and RQQs, at least considering the masses of their host dark matter haloes.

Chapter 3 presents a deep LOFAR observation of the NDWFS-Boötes field at 120-168 MHz. Differential source counts present a flattening below sub-mJy flux densities, which agrees with previous results from high- and low- frequency surveys. This flattening has been argued to be due to an increasing contribution of star-forming galaxies and faint active galactic nuclei.

In **Chapter 4**, we propose a method to select high- z quasars using the LOFAR observations presented in **Chapter 3**. The method combines optical/infrared color selection with 5σ LOFAR detections at 150 MHz to guarantee that stellar contamination in our sample is negligible. Furthermore, the depth of our LOFAR observations allow us to detect the radio-emission of quasars that otherwise would be classified as radio-quiet.

In **Chapter 5**, we use machine learning methods to compile a sample of quasars in the NDWFS-Boötes field to investigate the cosmic evolution of radio-selected quasars (RSQs) between $1.4 \leq z \leq 5.0$. Our results suggest that RSQs show evolutionary trends

that are similar to those exhibited by faint quasars ($M_{1450} < -22.0$). By comparing the spatial density of RSQs with that of faint quasars at similar redshifts, we find that RSQs may compose to up $31 \pm 22\%$ of the *total* (radio-detected and radio-undetected) faint quasar population.