Faint quasars at very low frequencies

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Chapter 1

Introduction

1.1 Quasi-Stellar objects: Short historical perspective

The development of radio-telescopes in the nineteen-sixties made this decade a golden age for astronomy. The first two important discoveries were the cosmic background radiation and pulsars. The third was that of quasars (acronym for quasi stellar radio source) by Dutch-American astronomer Maarten Schmidt. In 1963, Schmidt obtained the spectrum of the star-like object coinciding with the position of the radio source number 273 in the (3C) 3rd Cambridge Catalog of Radio Sources (Edge et al. 1959). The spectrum looked unlike the spectrum of any star because it contained broad-emission lines, unlike stellar spectra which contain narrow-absorption lines. **Even** more puzzling was the fact that the emission lines did not match any of the known chemical elements. Schmidt quickly realized that these lines corresponded to hydrogen emission lines, which were shifted towards the red end of the spectrum by a factor of 0.158, which corresponds to a receding velocity of one-sixth of the velocity of light (Schmidt 1963). The implicit distance indicates that the light from the source 3C273 had traveled by almost two billion years before reaching Earth. To be visible at such distances implies that 3C273 is very powerful and luminous, suggesting the operation of powerful energetic mechanisms unknown at the time of its discovery. Schmidt's pioneering work on the quasar 3C273 marked the beginning of a journey of discovery that continues until this day, with the number of quasars discovered continuously increasing, and the confirmation of that some already exist less than seven hundred million years after the big bang (Bañados et al. 2018).

The discovery of the first quasar represents a historic landmark in astronomy for several reasons. First, it is a superb example of the synergy between radio and optical astronomy leading to the discovery of a new class of astronomical objects. Secondly, until then, most cosmologists and astronomers believed in Fred Hoyle's steady state theory (Hoyle 1948), which proposes that the density of the universe remains unchanged during its expansion because new matter (stars and galaxies) is continuously being created. According to this theory, the expanded space refills with new stars and galaxies, so that the universe in the present is not different from how it was in the past and how it will be in the future. The discovery of distant quasars implies that the universe in the past looked different compared to the current universe. This implies that the universe is evolving, which contradicts the steady state theory. Thirdly, it was the basis of the recognition of ubiquitousness of black holes (BHs) in the universe, which are now an essential part of the theories and models of formation and evolution of galaxies and stars.

1.2 Quasar Properties

By the end of the sixties, Schmidt had studied a large sample of quasars and defined what he considered to be their properties: star-like morphology associated with a radio source, variable light, large UV flux, broad emission lines, and large redshift (Schmidt 1969). We now know that not every quasar has all of these properties. For instance, only a fraction ($\sim 10\%$ in traditional radio surveys) of the quasars can be associated with a bright radio counterpart. One property that is common though is their high UV rest-frame luminosity. Therefore it is possible to detect them at very large distances (and hence at earlier epochs). An important difference between stellar sources and quasars is their spectral energy distributions (SEDs). The former can be described approximately by single-temperature black-body SEDs, while the latter can be characterized roughly using a power-law SED.

The temporal variability of quasars was one of their first properties to be studied in detail (Matthews & Sandage 1963; Smith & Hoffleit 1963), and confirmed to be an important property of active galactic nuclei (AGN). The origin of temporal variability in quasars is still under investigation, however instabilities in the accretion disk or jets have been suggested as explanations. AGN variability can be exploited using a technique called reverberation mapping (RM) to probe the size and structure of the broad-line region (BLR), and to obtain estimates of the BH masses (Peterson 1988; Peterson et al. 2004). Using this technique, observing campaigns monitor the continuum and emission-line brightness of quasars; the time-delays between brightness measurements can be used to derive the size of the region where the emission-line comes from. Assuming that classical Newtonian mechanics describes the motion of gas in the vicinity of the central BH, its mass can be estimated using Kepler's laws. RM has provided good estimates for the BH masses of low-z quasars (e.g. Kaspi et al. 2000), but it is not suitable for high-redshift, high-mass BH sources due to the longer variability scales (Kaspi et al. 2004; Lira et al. 2018). Finally, assuming that the motion of the gas in the BLR is virialized, RM provides the basis to obtain estimates of BH masses of high-z quasars using single-epoch spectra (Kaspi et al. 2000; McLure & Dunlop 2004).

The presence of strong, broad emission lines is a defining characteristic of quasars. These emission lines include the hydrogen $\mathrm{Ly}_\alpha\ \lambda1215$, the hydrogen Balmer-series lines ($\mathrm{H}_\alpha\ \lambda6563$, $\mathrm{H}_\beta\ \lambda4861$, $\mathrm{H}_\gamma\ \lambda4340$), and prominent lines of abundant ions such as $\mathrm{Mg\,II}\ \lambda2798$, $\mathrm{C\,III}\ \lambda1909$, and $\mathrm{C\,IV}\ \lambda1549$. These spectral features (especially the Ly_α emission line) make the colors of quasars very different from those of galaxies and most stars. In practice, this implies that the majority of quasars can be identified using 3 broadband optical filters: one containing the Ly_α emission, one blueward (the dropout band), and one redward. In fact, a large fraction of the ~ 592000 quasars currently known (Flesch 2015) have been discovered using color selection.

The quasar population is also divided according to their radio properties. The majority of quasars (radio-quiet quasars, RQQs) have weak or absent radio emission, while a small fraction of $10-15\%$ have strong radio emission (radio-loud quasars, RLQs). RLQs are often associated with bright radio sources characterized by powerful collimated jets (Bridle et al. 1994; Mullin et al. 2008), while RQQs usually remain radio-undetected in wide-field shallow radio surveys (White et al. 2007; Shen et al. 2009). This division still remains a point of discussion. Some authors have found that RLQs and RQQs have very similar properties (e.g. McLure & Dunlop 2001; Dunlop et al. 2003; Barvainis et al. 2005; Rochais et al. 2014), while others have demonstrated that there are important differences between them (e.g. Sulentic et al. 2003, 2007; Sikora et al. 2007; Kratzer & Richards 2015).

1.3 Supermassive Black Holes

Supermassive black holes (SMBHs) are compact astrophysical objects with masses of $10^6 M_\odot \lesssim M \lesssim 10^9 M_\odot$. According to the theory of general relativity, SMBHs are capable of deforming spacetime in a that both matter and electromagnetic radiation cannot escape from inside them. BHs are found as a solution to the Einstein field equations (EFEs, Einstein 1916) that describe the gravitational field outside a spherical mass that has neither electric charge nor angular momentum (Schwarzschild 1916). A rotating uncharged BH can be described using the solutions to the EFEs obtained by Roy Kerr in 1963 (Kerr 1963). A few years after the publication of the discovery of the first quasar by Schmidt, Donald Lynden-Bell proposed that SMBHs are located at the center of galaxies, and are responsible for powering quasars (Lynden-Bell 1969). The presence of central SMBHs in galaxies provides a satisfactory explanation for many of the observational properties of quasars such as: their extreme bolometric luminosity due to radiation emitted from accreting matter into the BH, the rapid orbital motion of the filaments and gas clouds in the local vicinity of the BH that can explain the broadening of the emission lines, and the compact emission region and its related short time-scale variability.

1.4 Very Low-Frequency Radio Astronomy

Radio astronomy had its origins at very low-frequencies (10-300 MHz) with the serendipitous discovery of radio-emission coming from the Galactic center in 1933 by Karl G. Jansky, using an antenna designed to receive radio waves at a frequency of 20.5 MHz (Jansky 1933). In 1937, radio-engineer Grote Reber designed and built a steerable paraboloid reflector that enabled him to confirm Jansky's discovery (Reber 1940a,b), and to carry out the the first systematic radio-survey at 160 MHz (Reber 1944). In his radio contour maps, radio-emission is aligned with the shape of the Milky way and clearly its center is clear visible, along with concentrations towards the direction of the constellations Cygnus, Cassiopeia, Canis Major, and Sagitarius. Additionally, as mentioned earlier, low-frequency radio observations played a crucial role in the discovery of the first quasar by Schmidt (1963), who used the 3rd Cambridge Catalog of Radio Sources (Edge et al. 1959) deduced from observations by the Cambridge Interferometer operating at 159 MHz.

The pursuit of higher sensitivities and higher angular resolutions drove the development of radio-astronomy in the second half of the twentieth century towards frequencies above 1 GHz. At the beginning, this was an obvious choice to obtain higher resolutions, as the angular resolution of an interferometer is inversely proportional to its observing frequency. However, the main reason behind this bifurcated focus is that the Earth's ionosphere poses an additional challenge at low-frequencies. Electrons in the ionosphere disturb the incoming wavefronts causing a phase shift that increases linearly with wavelength (Kassim et al. 1993). In the conventional self-calibration (Pearson & Readhead 1984), it is assumed that the phase shifts across the field-of-view (FOV) are constant (not changing with direction) therefore it is possible to determine a phase correction for each antenna for each polarization that is valid for the entire FOV. The wide fields of low-frequency radio-telescopes imply that sources significantly separated within the FOV will have lines-of-sight through the ionosphere with different electron densities, and therefore their phase shifts differ. The assumption that the differential phase shifts across the FOV can be ignored breaks down, and simple self-calibration is not applicable.

The beginning of the twenty-first century witnessed a renewed interest in very low-frequency radio-astronomy. This was driven by advances in modern computing and radio-interferometry technology, development of new calibration algorithms, the scientific motivation of probing the relatively unexplored very low-frequency parameter space, and construction of the Square Kilometer Array (SKA, Schilizzi 2005). The SKA is the largest radio-telescope ever proposed, and will be built in Australia and several African countries including South Africa; and various SKA "pathfinders" projects operating at low-frequencies have been built to pave the way for the SKA. These projects include the Long Wavelength Array (LWA; Taylor 2007), the Murchison Wide-field Array (MWA; Lonsdale et al. 2009; Tingay et al. 2013), and the Low Frequency Array (LOFAR; van Haarlem et al. 2013). These radio-telescopes will serve as testbeds in which to evaluate the technologies, observing strategies, calibration algorithms, and computational challenges that will be eventually used in the construction and operation of the SKA.

Radio-telescopes such as the Jansky Very Large Array (JVLA) and Giant Metrewave Radio Telescope (GRMT) are based on a steerable antenna design, while LOFAR is based on phased-array technology. A phased-array radio-telescope is composed of stations that contain a certain number of dipoles at fixed orientation. Currently, (as of January 2018) there are thirty eight stations distributed across the Netherlands, with an additional thirteen stations located in Germany, France, United Kingdom, Ireland, Sweden, and Poland. There are 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 signals from each dipole are digitized and combined to create a digital beam. The fact that the beams are digital makes it possible to create different combinations of pointing directions and observing frequencies, limited only by the total bandwidth of the radio-telescope. Effectively, the large instantaneous FOV and multi-beam capabilities make LOFAR a powerful sky-survey machine.

Low-frequency radio-telescopes operate in a regime where ionospheric distortions have a significant impact on the observations. The lack of calibration algorithms that efficiently correct for ionospheric distortions is one of the difficulties that hindered the progress of low-frequency radio-astronomy in the past. In the last fifteen years, several direction-dependent calibration algorithms have been developed, including field-based calibration (Cotton et al. 2004), Source Peeling and atmospheric modeling (SPAM Intema et al. 2009; Intema 2014), SAGECal (Kazemi et al. 2011; Yatawatta et al. 2013), facet-calibration (van Weeren et al. 2016; Williams et al. 2016), and kMS/DDFacet (Tasse 2014; Smirnov & Tasse 2015; Tasse et al. 2018)

1.5 Outline of this thesis

Quasars represent the active phase of SMBHs, and are among the most luminous, powerful, and energetic objects known in the universe. The goal of this thesis is to use low-frequency and high-frequency radio observations to address the following questions:

- Is the radio loud/quiet quasar dichotomy real?
- Can deep low-frequency radio observations be used to effectively select high-z quasars?
- How does the faint radio-selected quasar population evolve with redshift?
- Is the environment of quasars related to the origin of their radio-emission?

In this thesis, the main tools used are low-frequency and high-frequency radio imaging, spectroscopic quasar catalogs, and ancillary optical and infrared data. Below there is a detailed description of the chapter contents.

In **Chapter 2**, we investigate the clustering properties of 45441 RQQs and 3493 RLQs drawn jointly from the Sloan Digital Sky Survey (SDSS, York et al. 2000; Schneider et al. 2010) and Faint Images of the Radio Sky at 20 cm (FIRST, Becker et al. 1995) in the range $0.3 < z < 2.3$. From the clustering properties, we deduce that RLQs in our sample inhabit massive dark matter haloes with masses of $M_{\rm DMH} \gtrsim 10^{13.5}\, h^{-1}\, M_{\odot}$ at all redshifts, which corresponds to the mass scale of galaxy groups and galaxy clusters. RQQs reside in less massive haloes of a few times $\sim 10^{12}\, h^{-1}\, M_{\odot}$. Additionally, the clustering signal shows a dependence on BH mass, with the quasars powered by the most massive BHs clustering more strongly than quasars having less massive BHs. These results suggest 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 radio-survey (with a central rms of $55\,\mu\mathrm{Jy}$) of the NOAO Deep Wide-field Survey (NDWFS) Boötes field (Jannuzi & Dey 1999) conducted with LOFAR at 120-168 MHz. This field has a large wealth of multi-wavelength data available. A total of 55 hours of LOFAR data have been calibrated using the directional-dependent calibration method presented by van Weeren et al. 2016. The final mosaic has an angular resolution of $3.98'' \times 6.45''$ and the resulting catalog contains 10091 radio sources (5σ limit) over an area of $20\,\mathrm{deg}^2$. Our differential source counts present a flattening below sub-mJy flux densities, which agrees with previous results from higher frequency surveys. This flattening has been argued to be due to an increasing contribution of star-forming galaxies and faint AGN. Moreover, the contribution of cosmic variance to the scatter in source counts measurements is evaluated. We find that the scatter due to cosmic variance is larger than the Poissonian errors of the source counts, and it may explain the discrepancies from previously reported source counts at flux densities $S < 1\,\mathrm{mJy}$.

Chapter 4 describes a method to identify candidate quasars that combines optical/infrared color selection with 5σ LOFAR detections at 150 MHz. This method is applied in a region of $\sim 9\mathrm{deg}^2$ located in the NDWFS-Boötes field using the LOFAR mosaic presented in Chapter 3, along with multi-wavelength data available for this region. The effect of the radio spectral index distribution on the selection of candidate quasars is investigated by combining the LOFAR observations with Westerbork Synthesis Radio Telescope (WSRT) imaging at 1400 MHz (de Vries et al. 2002). The candidate quasars detected by LOFAR and WSRT have a steep distribution of spectral indices with a median value of $\alpha_{150-1400\,\mathrm{MHz}} = -0.73 \pm 0.07$. For the candidates undetected by WSRT, we find an upper limit for the distribution of spectral indexes of $\alpha_{\mathrm{upp}} < -0.75$. As the upcoming LOFAR wide area surveys (Röttgering et al. 2011) are much deeper than the traditional 1.4 GHz surveys like NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995), the combination of LOFAR observations with optical/infrared imaging will be an excellent fishing ground fot obtaining large samples of quasars.

Chapters 2 and **4** demonstrate that the combination of optical, mid-infrared, and radio data can provide valuable insights into the SMBHs powering quasar activity. In this respect, **Chapter 4** capitalizes on the wealth of radio, optical, and mid-infrared data available and the ever-growing number of quasars to identify RSQs in the NDWFS-Boötes field. This provides a robust statistical sample to draw conclusions regarding the evolution of RSQs across cosmic time, and possible origins of their radio emission. The identification of faint RSQs is an essential step in understanding the radio-loudness distribution dichotomy in quasars.

In **Chapter 5**, we use machine learning (ML) algorithms to compile a sample of quasars to investigate the luminosity function of quasars detected by LOFAR (radio-selected quasars, RSQs). The sample comprises 134 objects, including both photometrically-selected candidate quasars (51) and spectroscopically confirmed quasars (83). The depth of our LOFAR observations allows us to detect the radio-emission of quasars that otherwise would be classified as radio-quiet. In our final sample, a fraction of 66% of the quasars are fainter than $M_{1450} < -24.0$, a regime where the luminosity function of RSQs has not been studied before. Our results agree with a pure luminosity evolution model at $z < 2.4$ and luminosity evolution and density evolution model at redshift $z > 2.4$. 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. This fraction, within uncertainties, seems to remain roughly constant with redshift.

1.6 Future prospects

The study of quasars is a very active field of research and will continue to be so in the years to come. Radio (LoTSS, Shimwell et al. 2018; FIRST, Becker et al. 1995), optical (SDSS, York et al. 2000; PanSTARRS, Chambers et al. 2016), mid-infrared (Spitzer; WISE, Cutri 2013), and spectroscopic (SDSS Schneider et al. 2010; BOSS Pâris et al. 2018; LAMOST, Yao et al. 2019; SHELLQs Matsuoka et al. 2016) surveys have already observed hundreds of square degrees in the Northern hemisphere, and will provide large samples containing hundreds of thousands of quasars, such as those used in this thesis. Future telescopes will have higher sensitivity, and will make it possible to further increase the number of known quasars. Planned surveys with facilities such as the Large Synoptic Survey Telescope (LSST, Ivezić et al. 2019), 4MOST (de Jong et al. 2012), Dark Energy Spectroscopic Instrument (DESI, DESI Collaboration et al. 2016), Square Kilometre Array (SKA, Schilizzi 2005), Wide Field Infrared Survey Telescope (WFIRST, Spergel et al. 2015) and Euclid **(Laureijs et al. 2011)** will expand the number of known quasars at all redshifts to the order of millions. This will open a new unexplored parameter space for the study of quasar activity. It is expected that observations obtained with these surveys will have an important role in addressing many of the open questions regarding quasars. Some of these include: when the first quasars were formed?, what is the nature of faint quasars?, and what is the role of quasars in cosmic reionization?.