



A Catalog of Active Galactic Nuclei from the First 1.5 Gyr of the Universe

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Active galactic nuclei (AGN) are prominent astrophysical objects that can be observed throughout the whole Universe. To understand the underlying physical processes and the different appearance of AGN types, extensive samples are needed. Nowadays, various AGN catalogs are available at different wavebands. However, at the highest redshifts data are still relatively sparse. These data are required for examining AGN properties in the early Universe. This way we can compare the earliest AGN with those seen at lower redshifts, and can study their cosmological evolution. Additionally, because of their high luminosity, AGN may also be used as probes to test cosmological models. With the aim of constructing a complete sample of all known AGN at $z \geq 4$, we are currently compiling a photometric catalog from literature sources. We cross-match catalogs particularly at optical and radio wavebands, to build up a sample for detailed high-resolution radio interferometric studies. The continuously updated list now contains nearly 2,600 objects with known spectroscopic redshifts, optical magnitudes, and auxiliary information about observations at other wavebands. About 170 of them are known radio sources for which we collect existing radio interferometric data from the literature.

Keywords: quasars, active galactic nuclei, extragalactic astronomy, photometry, spectroscopy, catalogs

1. INTRODUCTION

Active galactic nuclei (AGN) have been extensively studied for more than half a century. The activity of AGN is believed to originate from material falling into an accreting supermassive black hole (SMBH) in the central region of the galaxy, as first proposed by Lynden-Bell (1969). Due to the accretion process, enormous amount of energy is released, which can be observed throughout the entire electromagnetic spectrum (e.g., Urry and Padovani, 1995). In the cases of radio-loud (jetted) AGN, strong radio emission is produced via synchrotron emission in a symmetric pair of jets emanating from the vicinity of the central SMBH (Blandford and Rees, 1974; Blandford and Königl, 1979). However, the formation and physical properties of AGN are not yet fully understood (e.g., Netzer, 2015).

The large variety of observed characteristics of AGN require sophisticated models to provide an adequate description of the underlying physics. To determine their properties satisfactorily, we need both low- and high-redshift populations of AGN, which requires statistically complete samples.

To date, several different AGN catalogs and samples exist at various wavebands (e.g., Constantin et al., 2009; Véron-Cetty and Véron, 2010; Shen et al., 2011; Kalfountzou et al., 2014; Secrest et al., 2015). We are currently compiling a catalog using extensive samples of AGN primarily discovered by optical observations in recent years, with the aim of constructing a complete sample of AGN at the earliest epochs of the Universe. Given the accelerating pace of data acquisition of

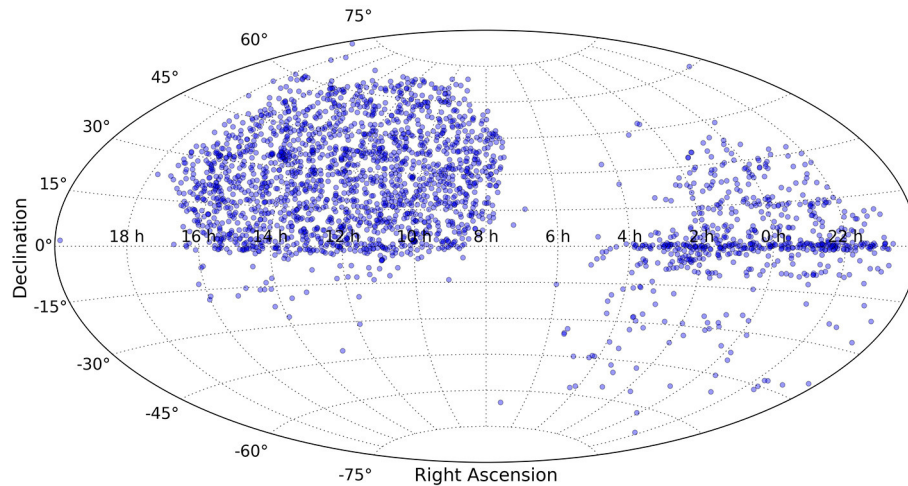


FIGURE 1 | Sky coverage of the sources at the current state of the catalog.

contemporary optical sky surveys, we intend to update and extend our catalog regularly.

To better understand the observable characteristics of AGN, we collected available data at radio wavebands as well, including flux densities from large radio surveys and interferometric observations of individual objects. Our catalog may facilitate several scientific studies. The future applications carry the opportunity to determine the luminosity function of AGN at the highest redshifts (e.g., Fan et al., 2004; Willott et al., 2010; Jiang et al., 2016). It can also provide sample for studies of galaxy environment and possible overdensities around high-redshift quasars (e.g., Orsi et al., 2016; Uchiyama et al., 2017). With supplementary UV data, it may become useful for cosmological studies, providing a sample where ‘standard candles’ can be selected from (e.g., Marziani and Sulentic, 2014). Likewise, using a sample of the most distant compact radio-emitting AGN, further constraints on the angular size–redshift relation could be obtained (e.g., Gurvits et al., 1999). Presumably, it will make the planning of interferometric observations for sufficiently bright radio sources simpler. Furthermore, it might aid in the selection of interesting individual objects for detailed analysis, and in examining the Galactic foreground in different wavebands.

To compile our sample of high-redshift AGN, we applied a somewhat arbitrary $z \geq 4$ threshold for redshifts. In this regime, the first AGN (QSO 0046–293) was discovered by Warren et al. (1987). Since then, the known number of sources at the earliest epochs of the Universe increased at a fast pace, primarily due to extensive all-sky surveys, e.g., the Sloan Digital Sky Survey (SDSS) (York et al., 2000; Eisenstein et al., 2011; Alam et al., 2015).

2. COMPILING THE CATALOG

We built the base of the catalog using 3 large samples of AGN: the quasars of the twelfth data release of SDSS (Jiang et al., 2016; Pàris

et al., 2017), the high-redshift quasar sample (Bañados et al., 2016, and references therein) of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, Chambers et al., 2016) Survey and the Half Million Quasars (HMQ) Catalog (Flesch, 2015). We filtered the HMQ and SDSS quasars for redshifts $z \geq 4$. Since sources in the Pan-STARRS high-redshift quasar sample had redshifts $z \geq 5.6$, no filtering was needed.

The bulk of the catalog was then constructed after cross-matching the three large samples above. First, HMQ and SDSS quasars were matched. To avoid duplicate entries, we were looking for SDSS-discovered objects in the HMQ sample. Based on the results of e.g., Barro et al. (2011) and Rimoldini et al. (2012), we applied a search radius of $1''$ and considered the objects within this radius identical if found in both catalogs. There were 2,363 objects in the HMQ catalog and 1,881 in the SDSS quasar sample at $z \geq 4$. All but 2 SDSS sources were also included in the HMQ sample. The match therefore resulted in 2,365 independent sources. Then the HMQ–SDSS sample was cross-matched with the Pan-STARRS quasar list, applying the same search radius of $1''$. This increased the number of unique sources to 2,470. The cross-matching and the concatenation of independent source lists were carried out using the `topcat` catalog editing software¹ (Taylor, 2005).

The resulting catalog contained the following properties: right ascension and declination (optical) coordinates, name, radio identification and X-ray identification names (when existing), redshift, optical magnitudes if known, and literature references regarding discovery and redshift data.

In the course of catalog updates, we added 121 new sources to the list. These were found in the literature (McMahon et al., 2002; Richards et al., 2009; Yi et al., 2014; Wang et al., 2016; Khorunzhev et al., 2017; Matsuoka et al., 2017; Reed et al., 2017; Tang et al., 2017; Tuccillo et al., 2017; Wang et al., 2017; Yang et al., 2017; Yi et al., 2017) but not contained in the 3 large catalogs

¹<http://www.starlink.ac.uk/topcat/>

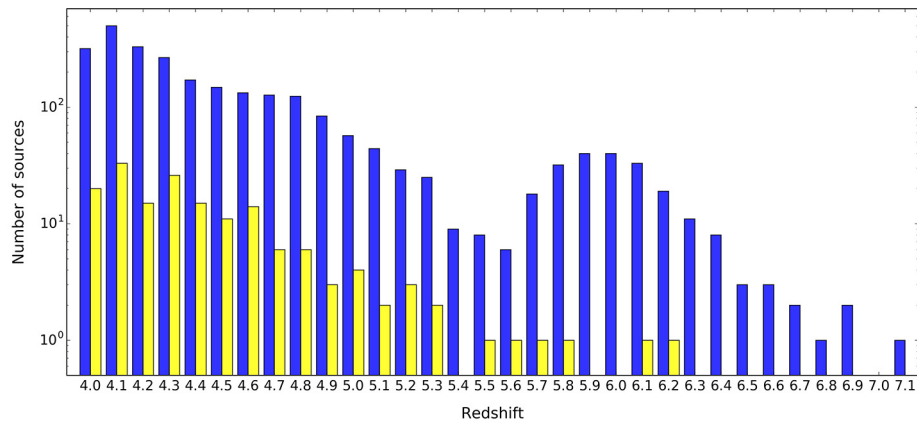


FIGURE 2 | Histogram of the redshift distribution of catalog entries, with a bin width of 0.1. Blue columns indicate all AGN in the sample, while yellow columns show the distribution of sources with available radio flux densities. From the total of 2,591 sources, 166 are detected in FIRST or (if out of FIRST coverage) in NVSS. Two thousand one hundred and forty-eight positions are covered by FIRST but radio sources not detected (brightness upper limit is available only). Two hundred and fifty two sources are outside the FIRST field and lack detection in NVSS, and 25 are outside the footprints of both surveys.

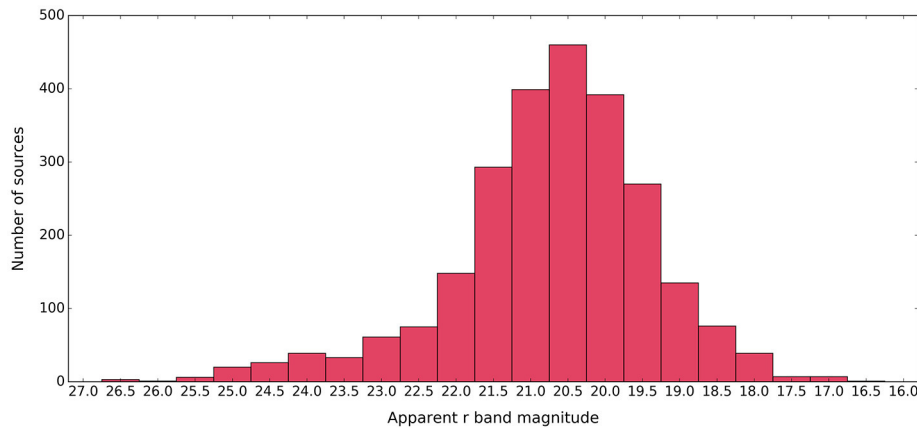


FIGURE 3 | Apparent red magnitude distribution of the high-redshift AGN. The histogram shows the 2,493 sources with available red magnitudes with a bin width of 0.5^m . Note that since most sources have photometry based on POSS plates, magnitudes might differ from SDSS magnitudes, up to $2^m - 3^m$.

that form the basis of our list. The sky coverage of the full sample is plotted in **Figure 1**.

To find radio counterparts, we searched for the catalog sources in the VLA Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) Survey² (White et al., 1997) database with a $1.5''$ radius, the same value that was applied by Ivezić et al. (2002). This resulted in 144 matches. We also marked those 2,148 positions which were covered by FIRST but there were no sources found above the detection limit (~ 1 mJy), and those which were close to the field edge or lay outside FIRST coverage. Those which were outside the FIRST footprint, were also searched in the NRAO VLA Sky Survey (NVSS) catalog³ (Condon et al., 1998), with a search radius of $10''$ (Sadler et al., 2002). Positions outside the NVSS field or both survey footprints were also noted. Altogether 166 sources have radio flux densities measured in

either FIRST or NVSS, both at 1.4 GHz. This is 6.5% of the 2,566 sources which were covered by either of the surveys. The redshift distribution of the full sample and of those sources with radio detection are plotted in **Figure 2**. The prominent “gap” visible between redshifts 5.3 and 5.6 and the excess in the 5.7–6.4 range arises mainly from the sample selection: the Pan-STARRS sample contained only quasars with $z \geq 5.6$. Moreover, the Pan-STARRS survey has a more extensive sky coverage than SDSS: the majority of independent Pan-STARRS quasars have redshifts between 5.7 and 6.4.

We added very long baseline interferometry (VLBI) flux densities for a total of 35 quasars (Paragi et al., 1999; Beasley et al., 2002; Frey et al., 2003, 2005, 2008, 2010, 2011; Fey et al., 2004; Momjian et al., 2004, 2005, 2008; Romani et al., 2004; Petrov et al., 2006, 2008; Helmboldt et al., 2007; Veres et al., 2010; Cheung et al., 2012; Frey et al., 2013; Cao et al., 2014, 2017; Parijskij et al., 2014; Frey et al., 2015; Gabányi et al., 2015; Coppejans et al., 2016; Wang et al., 2017; Zhang et al., 2017). We also marked sources

²<http://sundog.stsci.edu>

³<http://www.cv.nrao.edu/nvss/>

that have already been proposed for VLBI observations to our knowledge.

From the total of 2,591 AGN in the current version of our catalog, we have available red band optical magnitudes for 2,493 quasars. To illustrate this, the distribution of the r band magnitudes of these sources are shown in **Figure 3**. A descending trend can be seen at the faint end of the histogram due the selection effect caused by the limited sensitivity of the optical surveys. The histogram also shows that there are a couple of particularly bright sources in the sample. Given the high redshifts, these magnitudes would imply extremely high luminosities for these AGN. We therefore investigated this peculiarity by looking at individual objects in our catalog. We found that in some cases sources from the HMQ catalog where the photometry was based on Palomar Observatory Sky Survey (POSS) plates show significant difference from the values observed in SDSS, reaching up to $2^m - 3^m$. However, the original HMQ catalog contains a flag indicating the quality of the photometry. We plan to improve our catalog and make sure that only high-quality photometric data are listed in the next version.

3. SUMMARY

With the aim of creating a catalog which can be applied to a wide range of studies, we cross-matched and concatenated 3 large lists of AGN, taken from the SDSS twelfth data release, the Pan-STARRS first data release, and the HMQ catalog. We expanded this base catalog with numerous sources from the literature. The sample counts 2,591 sources at its current state, from which 166 AGN have available measured radio flux densities. Furthermore, 35 of them already have high-resolution VLBI imaging observations published in the literature. The current version of the catalog can be obtained on request by contacting the corresponding author. We intend to make the $z \geq 4$ AGN catalog publicly available in the near future.

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AUTHOR CONTRIBUTIONS

KP compiled the catalog. All authors participated in defining the catalog content and the preparation of the manuscript.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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