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The Washington Multi-AGN Catalog: Data Release 0.1 (Internal USNO Use)

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1. SAMPLE CONSTRUCTION AND SCOPE

DR 0.1 of the WMAGN catalog consists of multi-AGN systems culled from the literature from the year 1970 up to 2010 (effectively 1970-2009), and are derived from two classes of literature: (1) papers focusing on a single system (e.g. the dual AGN in NGC 6240 reported by Komossa et al. 2003) or papers which focus on a small sample of objects (e.g. the small search for lenses by Miller et al. 2004), and (2) large systematic searches for multi-AGN systems or candidate systems (e.g. Hennawi et al. 2006).

DR 0.1 focuses on four classes of multi-AGN systems:

- **'Binary Quasars' and candidates**
- **Dual AGNs and candidates**
- **Binary AGNs/SMBHs and candidates**
- **Recoiling AGNs/SMBHs and candidates** (post-coalescence)

Throughout this technical report we will refer to this terminology and implicitly include candidate systems when referring to any one class of objects.

DR 0.1 does *not* include:

- Confirmed gravitationally lensed systems
- Projected pairs of quasars/AGNs (i.e. quasars with discordant redshifts)

Projected pairs of quasars or AGNs with significantly different redshifts are not scientifically relevant for the present catalog, which focuses on physically associated multi-AGN systems. Gravitational lenses were excluded in order to narrow the focus of the first data release, but may be included in future data releases. This decision was one made out of necessity: the volume of multi-AGN literature (without including gravitational lenses) already prohibited us from pushing beyond 2009 in the literature, and inclusion of gravitational lenses would have severely delayed the present release.

Following the convention adopted in Hennawi et al. (2006), in this data release we define physically associated AGNs as having line of sight velocity differences of $|v_{\rm LOS}| \lesssim 2000\,{\rm km\,s^{-1}}$ and projected separations of $< 1\,{\rm Mpc}$. This definition is by no means conservative, and in fact studies of dual AGNs – such as Liu et al. 2011b – require much more stringent velocity differences of $|v_{\rm LOS}| \lesssim 600\,{\rm km\,s^{-1}}$ and projected separations of $< 100\,{\rm kpc}$; our operational definition is likely to change in future releases in order to accommodate more physically motivated nomenclature (see Section 3).

1.1. *Methodology*

Multi-AGN systems included in this release of the catalog were identified in essentially two ways: (1) via a systematic search of NASA ADS for relevant literature and (2) 'accidental' findings of relevant literature. Our systematic search of NASA ADS involved using a variety of aliases for each of the four classes mentioned above in order to recover any papers which mentioned said aliases within their text; the aliases we used are listed for the reader in Table 2 in the Appendix. This systematic search returned over 1200 observational and theoretical works, which then needed to be further parsed to exclude articles that were unrelated to multi-AGN discoveries (as one example: theory papers on pulsar timing arrays). This systematic method of culling the literature, as it turned out, often missed a significant portion of literature articles due simply to the number of naming conventions and aliases used in these research fields (many of which were not included in our original search criteria). In fact, a significant portion of articles were found 'accidentally' within the in-text citations or ADS citation lists during the review of articles we had already found; we back-tracked many times and added aliases to our list. At present count, the combination of the systematic searches and accidental findings has resulted in roughly 500-600 relevant multi-AGN papers between the years 1970-2020 (this does, however, include some articles on gravitational lenses, which are not a focus at this time). Of these 500-600 articles, roughly 150

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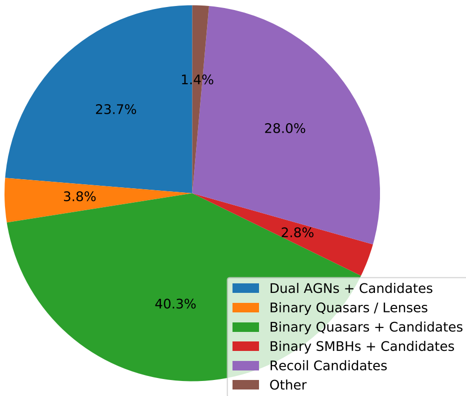

Figure 1. The breakdown of system types in WMAGN DR 0.1. The majority of systems within WMAGN DR 0.1 are binary quasars ($\sim$ 40%), followed closely by dual AGNs ($\sim$ 24%) and recoil candidates $\sim$ 28%). Binary SMBHs, quasars that may be lenses, and 'other' systems make up a minority of the catalog. We define 'other' systems as those which have been classified as more than one type.

papers make up this current data release for 1970-2009. The following two sections briefly describe the various literature sources from which we selected the multi-AGN systems. The catalog was constructed using a Jupyter Notebook and is available upon request. We touch more on the issue of naming conventions in Section 3.

1.2. *Individual Targets from the Literature*

A total of 55 unique systems (which do not overlap with the catalogs discussed below) were found in papers focusing on individual objects and small samples of objects; a further three individual systems were first identified in individual papers, but these overlap with the large systematic searches described below. The unique 55 systems include objects from each of the four classes of objects mentioned above. When possible, information on these individual targets are adding to a comma separated value file manually, which is read into the Jupyter Notebook for later matching and concatenation with the matched catalog entries.

1.3. *Catalogs from the Literature*

1.3.1. *Hennawi et al. (2006)*

This paper assembled a sample of 221 binary quasars across the redshift range $0.5 \lesssim z \lesssim 3.0$ – selected from the Sloan Digital Sky Survey (SDSS) and the 2DF QSO Redshift Survey and confirmed through follow-up optical spectroscopic observations – with line-of-sight velocity differences $|v_{\rm LOS}| \lesssim 2000\,{\rm km\,s^{-1}}$ and projected separations of $< 1\ {\rm h^{-1}}$ Mpc, where they have factored out their adopted value of little $h = 0.72$. This work provides a total of four tables: (1) color-selected binary quasars confirmed via follow-up spectroscopy, (2) lens-selected binary quasars confirmed via spectroscopy, (3) binary quasars discovered via spectroscopic observations provided by overlapping SDSS and/or 2DF plates (thus circumventing any fiber collision issue), and (4) projected quasar pairs. While the color-selected, lens-selected, and overlapping plate samples of binary quasars offered unique entries to the catalog, a few systems were accidentally included in the projected quasar pair table despite satisfying the binary quasar definition set forth by Hennawi et al. (2006). We have combined all of these tables together and have removed (a) true projected quasar pairs and (b) duplicate entries that appear in more than one table. We note that the nomenclature of Jhhmm+ddmmA,B is not consistent for all duplicate entries, i.e. in some cases source A in one table appears as source B in another table. We have identified and accounted for these cases, prioritizing the nomenclature established in Hennawi et al.'s Tables 2-4 (color, lens, and overlapping plate selected binaries) over that in Table 8 (the projected pairs). There is some overlap between this sample and the other catalogs and individual objects included in this release, which we account for within our own catalog.

1.3.2. *Cheung (2007)*

This paper focuses on AGN systems with winged or X-shaped radio morphologies, which has in the past been suggested to arise due to the fast realignment of radio jets following the merger of two SMBHs (e.g. Merritt & Ekers 2002). The first table provided is a list of 17 known X-shaped or winged radio systems from the literature, while the second table provided a list of 100 X-shaped or winged radio source candidates. These radio selected sources likely trace the recoiling AGN/SMBH regimes, if they do indeed arise from mergers of binary SMBHs. Many of these sources are currently missing redshift entries; a future release will attempt to fix this issue of missing redshifts.

1.3.3. *Myers et al. (2007, 2008)*

Myers et al. (2007) constructed a sample of 111 photometrically selected binary quasar candidates from SDSS DR4 using the kernel density estimation technique of Richards et al. 2004 (which relies on SDSS five-band photometry). These 111 pairs appeared in a single table in Myers et al. (2007). While a subsample of these pairs were previously known binary quasars and/or lens candidates (which possessed known spectroscopic redshift measurements), the vast majority of the KDE selected

SDSS quasar pairs possessed only photometric redshifts. We removed during our first pass the previously known binaries that possessed spectroscopic redshifts in the catalog (these objects were flagged within the Myers et al. table and their spectroscopic redshifts were listed).

Myers et al. (2008) re-examined a subset of the putative (photometrically-selected) quasar pairs by obtaining follow-up optical spectroscopic measurements for 27 pairs. Their results fall into four categories (and, consequently, primarily across four tables): (1) Systems for which spectroscopic observations were obtained for one out of two quasars in a pair, (2) confirmed binary quasars, (3) confirmed projected quasar pairs, and (4) ambiguous pairs for which spectroscopic observations could not definitively rule out a lens hypothesis. Additionally, the authors included in a fifth table a list of previously known binaries, projected pairs, and lenses that were included in the original 2007 sample and for which other literature articles have deduced the system properties from follow-up observations.

As we prefer spectroscopic redshifts over photometric redshifts, we adopt all available spectroscopic redshifts listed in the tables of Myers et al. (2008). Upon matching the 2007 and 2008 catalogs together, we removed confirmed lens systems as well as confirmed projected pairs which were known previously or discovered via the optical spectroscopic observations of Myers et al. During the matching process, we found that the naming convention was not completely consistent between the two catalogs; while the 2007 catalog refers to objects using their full SDSS designation (Jhhmmss.s+/ddmmss.s) and uses two columns, SDSS1 and SDSS2, to list the names of each object within a pair, the 2008 catalog uses one of two naming conventions for each pair: (1) the full SDSS designation, as in Myers et al. (2008), ***or*** (2) an 'Jhhmm+ddmmA,B' naming format akin to that used in Hennawi et al. (2006). We found that the 'Jhhmm+ddmmA,B' system components did *not* always map consistently to the SDDS1 and SDSS2 naming conventions used in the 2007 table (for example, we did not always find that SDSS1:A and SDSS2:B), and this issue therefore required careful matching on columns and indices in order to reassign each counterpart their associated spectroscopic redshift. It is unclear why this change in nomenclature occurred. Beyond the known binaries already excluded from the 2007 table, no other pairs reappear in the other literature articles or catalogs.

After the final matching and reorganization of the Myers et al. catalogs, we split the sample into spectroscopic binary quasars / candidates and photometric quasar binary candidates. We include the photometric candidates in this data release but in a separate table and, due to the lack of certainty in the component redshifts, we do not calculate line-of-sight velocity differences, redshift differences, etc.

1.3.4. *Kirkman & Tytler (2008)*

Kirkman & Tytler (2008) obtained spectroscopic observations for a sample of 130 QSO pairs for a study on Ly-α forest HI absorption. Having drawn these QSO pairs from a list of known QSOs at the time (presumably from NED) with NED magnitudes less than 22, the sample includes QSO pairs with a large range of angular separations and velocity differences, with a large portion of the study relying on projected pairs of quasars at discordant redshifts. While the projected pairs are not relevant for our purposes, the close pairs with smaller velocity differences have been included in our catalog. Overlap existed between this catalog and that of Tytler et al. (2009) (see below), and we found that the redshift measurements between the catalogs were not always consistent. For the time being, when matching the catalogs, we have arbitrarily deferred to the redshift measurements in Kirkman & Tytler (2008), though in a future release it would be prudent to obtain the latest redshift measurements from NED or Simbad for these objects.

1.3.5. *Tytler et al. (2009)*

In a study on metal absorption systems, Tytler et al. (2009) obtained spectroscopic measurements of a sample of 310 QSO pairs and triplets (drawn from a list of all known QSO pairs at the time), where 130 of these pairs overlapped with the Kirkman & Tytler (2008) sample. As with Kirkman & Tytler (2008), the pairs and triplets occupy a large parameter space of angular separations, redshift distributions, and velocity differences, with a large portion of the sample being made up from projected pairs of QSOs. However, we adopt the pairs with the smaller velocity differences and projected separations of < 1 Mpc. As discussed above, we matched this catalog to that of Kirkman et al., adopted the available redshifts listed in Kirkman et al., and then removed the duplicate entries.

1.3.6. *Wang et al. (2009)*

Wang et al. (2009) selected 87 candidate kpc-scale dual AGNs based upon the presence of double-peaked [OIII] spectroscopic emisson lines observed in the SDSS $3''$ fibers. While we now know that the vast majority of double-peaked optical sources are not, in fact, dual AGN, early work used this selection technique to find large samples of candidate systems. Future data releases will shed more details on these candidate systems, as a

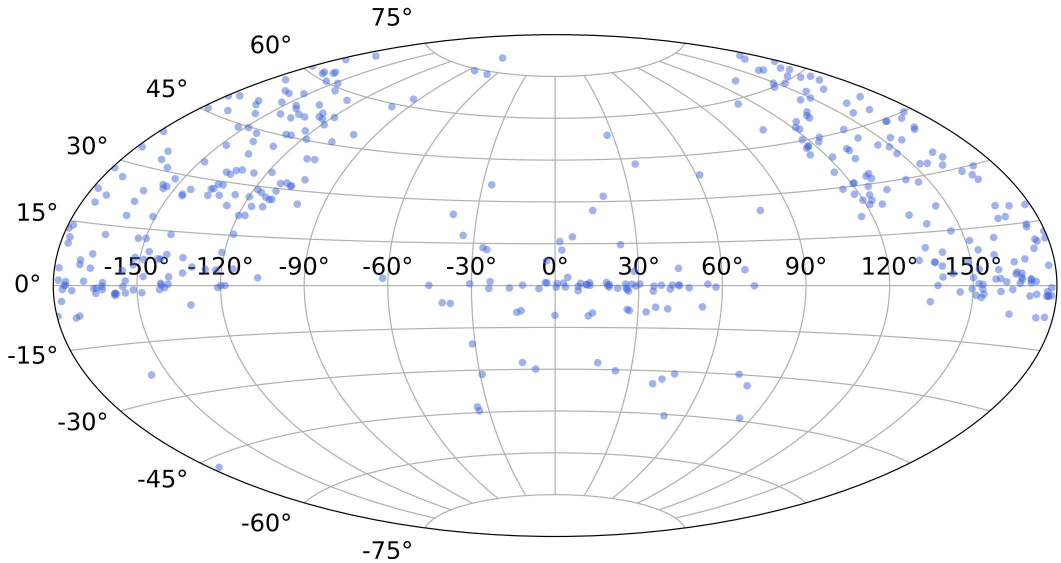

Figure 2. Sky distribution of WMAGN DR 0.1 systems.

large amount of follow-up work has been performed for double-peaked dual AGN candidates in recent years.

1.4. *Catalog Matching*

Catalog and object matching was performed in a Jupyter Notebook using the Pandas and Astropy packages. Studies for which there were multiple tables of data, such as Hennawi et al. (2006), saw those tables concatenated and reformatted to remove irrelevant information, duplicate entries, and add in information about the paper itself (such as the BibCode and DOI). Catalogs were matched together one-by-one using a match tolerance of $5''$; when possible, duplicate entries were accounted for by appending the BibCode and DOI of the second paper in which the duplicate appeared. As described above, many instances of errors or mismatched nomenclature were resolved manually by reassigning values, such as redshifts, via column and row indexing. We note that during the matching process between the Kirkman et al., Tytler et al., and Hennawi et al. catalogs, we defferred to the measurements in the Hennawi et al. catalog due to the observed discrepancies in redshifts between the Kirkman et al. and Tytler et al. catalogs.

2. DR 0.1 SAMPLE

WMAGN DR 0.1 comprises 422 systems with spectroscopic redshifts – and a further 63 systems with only photometric redshifts – published in the literature between 1970-2009, and fall into the four categories of (1) binary quasar, (2) dual AGN, (3) binary AGN/SMBH, and (4) recoiling AGN/SMBH, as well as candidates of each category; we show the breakdown of this sample into the specific classes in Figure 1. Recall, these systems satisfy the criteria of: $|v_{\rm LOS}| \lesssim 2000\,{\rm km\,s^{-1}}$ and projected separations of $<$ 1 Mpc. The majority of multi-AGN systems are binary quasars, followed by dual AGNs and recoil candidates, while binary SMBHs and systems which lack a definitive class make up a minority in the catalog. We show the sky distribution of DR 0.1 in Figure 2; since a significant portion of the multi-AGN systems arise from systematic searches of SDSS, a large number of sources overlap the SDSS field.

At a glance, binary quasars are predominantly selected and confirmed via optical imaging and optical spectroscopic measurements, while confirmed dual AGNs are overwhelmingly the result of high spatial resolution X-ray observations rather than optical spectroscopy. A combination of optical spectroscopic measurements and radio observations are predominantly used to search for signatures of binary AGNs/SMBHs or recoiling AGN candidates. The selection and confirmation techniques used to identify these various objects warrant more discussion and will be a focus for future releases. Currently, the catalog includes table entries for the selection and confirmation methods of each system, although last minute changes to the catalog structure has caused some confusion for these column entries of the individually identified pairs; this issue will be fixed before the next release.

The DR 0.1 redshift distribution (Figure 3) extends from $0 \lesssim z \lesssim 4$, with different classes of objects con-

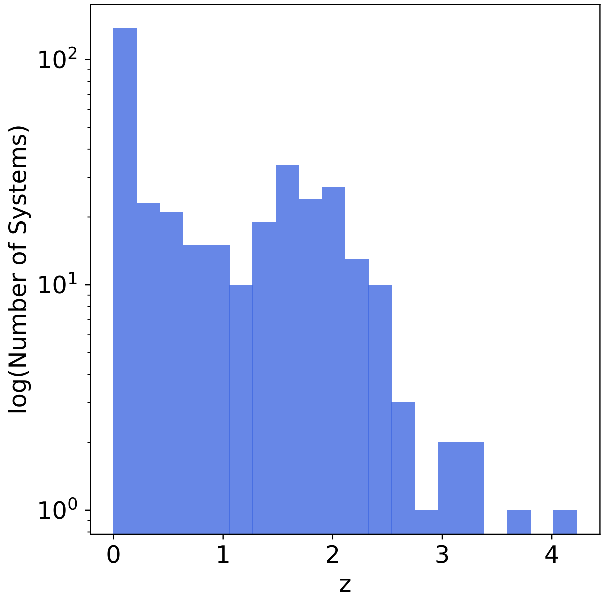

Figure 3. The redshift distribution for WMAGN DR 0.1. The x-axis shows redshift while the logarithmic y-axis shows the number of objects per redshift bin.

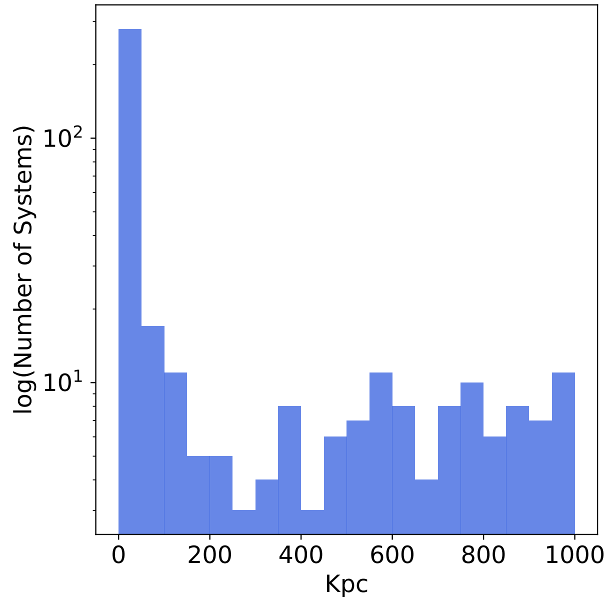

Figure 4. Projected separations of multi-AGN systems in WMAGN DR 0.1. The x-axis shows the projected separations of the multi-AGN systems in units of kiloparsecs, while the logarithmic y-axis shows the number of systems per separation bin.

tributing to different portions of that distribution. Dual AGNs and recoil candidates make up the majority of local redshift ($z \lesssim 0.5$) sources in the catalog, while binary quasars make up the wide distribution of sources from $0.5 \lesssim z \lesssim 4$.

As with the redshift distribution, the different classes of objects typically contribute to different portions of observed distribution of projected separations, shown in Figure 4. Dual AGNs and recoil candidates contribute the most to the large spike in projected separations $0 \lesssim (r_{\rm p}/{\rm kpc}) \lesssim 100$, while binary quasars exhibit very small *and* very large projected separations; binary quasars are the sole contributor to the distribution beyond $r_{\rm p} \gtrsim 100$ kpc. We note that many of the dual AGN candidates and recoil candidates have only upper limits or pegged values for their projected separations. For instance, for the double-peaked [OIII] selected dual AGN candidates from Wang et al. (2009), we have assumed $3''$ angular separations as an upper limit, since these objects are selected based upon their double-peaked spectroscopic emission lines observed via the $3''$ SDSS fibers. The upper limit of $3''$ is then used to derive projected separations in kpc at the redshift of each source. For recoil candidates we have assumed a separation of $0''$ and 0 kpc since these objects are the result of *mergers* of SMBHs. We use an upper limit of 200 pc for SMBH binary candidates which lack any constraint in terms of projected separation; 200 pc is likely far larger than the orbit diameter of any true gravitationally bound pair, and this can be adjusted accordingly in a future release.

The completeness of this sample is limited by the completeness of the literature; that is to say, the sample in this data release is highly *incomplete* because the selection methods used to identify multi-AGN systems are intrinsically incomplete[1]. However, in terms of the *known* multi-AGN systems (published in the literature between 1970-2009), we can be confident that we are at least 90% complete, meaning that this release includes 90% of all known multi-AGN systems and that, at worst, we have missed ~ 53 known systems from the literature from the years 1970-2009. Identification of any missed systems will be one of the focuses of future data releases.

2.1. *Known ICRF Targets*

Matching the DR 0.1 catalog with the ICRF3 catalog ($1''$ tolerance) yields an overlap of 18 targets (which are spectroscopically confirmed at similar redshifts), and we list the system types, literature names, angular separations, and ICRF designations of these 18 systems in Table 1.

3. LACK OF UNIFORMITY IN THE LITERATURE

[1] The reasons for the lack of completeness in the literature as a whole are beyond the scope of this report.

Table 1. ICRF3 Targets within WMAGN DR 0.1

System Type	Literature Name	Separation (")	ICRF Designation
Binary Quasar	SDSSJ0812+2520A	105.8	ICRF J081247.7+252242
Binary Quasar	J13488.7+28407.0	59.09	ICRF J134804.3+284025
Recoil Candidate	J1357+4807	0.0	ICRF J174614.0+622654
Recoil Candidate	J1424+2637	0.0	ICRF J142440.5+263730
Dual AGN / Quasar Candidate	PKS 1614+051	6.55	ICRF J161637.5+045932
Binary Quasar	PKS 1145-071	4.2	ICRF J114751.5-072441
Binary SMBH Candidate	Arp 102B	0.4104	ICRF J171914.4+485849
Binary SMBH Candidate	OJ 287	2.2146E-5	ICRF J085448.8+200630
Binary SMBH Candidate	3C 120	3.0379E-5	ICRF J043311.0+052115
Binary SMBH Candidate	OX 169	0.05835	ICRF J214335.5+174348
Binary SMBH Candidate	3C 390.3	0.1725	ICRF J184208.9+794617
Binary SMBH Candidate	1928+738	3.0E-6	ICRF J192748.4+735801
Binary SMBH Candidate	3C 66B	0.4598	ICRF J022311.4+425931
Binary Quasar Candidate	PKS 0537-441	3.9	ICRF J053850.3-440508
Binary SMBH	CSO 0402+379	0.0068	ICRF J040549.2+380332
Binary SMBH Candidate	3C 345	3.0084E-6	ICRF J164258.8+394836
Binary SMBH Candidate	SDSS J1048+0055	0.0025	ICRF J104807.7+005543
Binary Quasar	SDSSJ1310+0044A	65.5	ICRF J131028.5+004408

Note—**ICRF3 targets identified within the WMAGN DR 0.1**. Column 1: System type. Column 2: Literature name adopted in WMAGN DR 0.1. Column 3: Angular separation in arcseconds. Column 4: ICRF3 designation.

Throughout the process of assembling the relevant literature sources for this catalog, it became clear that the research field of multi-AGNs is often times neither well-documented nor uniform in terms of nomenclature and definitions. We have included the large list of aliases we have used to find multi-AGN literature articles in Table 2.

The term 'binary quasar' has been used rather loosely for decades and can be used to refer to not only (a) quasar pairs with small angular separations and similar redshifts but also (b) quasar pairs with similar redshifts but **large** angular and projected separations. In many cases, these so-called 'binary quasars' may not be physically associated at all despite the terminology used to describe them. To make matters more complicated, many authors use a variety of aliases for 'binary quasar,' (as one example: 'double quasar'), and these aliases can further confuse physically associated and unrelated pairs of quasars.

A similar problem arises in the dual AGN and binary SMBH literature. Early literature articles in the 2000s used the terminology of 'binary AGN' and 'dual AGN' interchangeably, and while the terminology has slowly evolved so that 'binary SMBH' refers to a *gravitationally bound* pair of SMBHs and 'dual AGN' refers to two active nuclei in a pair of physically associated galaxies (or a post-merger), the physically-motivated terminology has not been clearly and authoritatively defined in the literature[2]. Even with the progressive evolution of dual AGN terminology, we run into the same problem as with the 'binary quasar' terminology: researchers use myriad aliases to classify or define the nature of multi-AGN systems that fall into the categories of 'dual AGN' or 'binary SMBH,' and this can lead to significant problems when trying to retrieve a complete account of the literature. As one example: we included the dual AGN AM1211-465 identified by Jiménez-Bailón et al. (2007) in WMAGN DR 0.1, but this dual AGN was *not* identified through our systematic NASA ADS search because Jiménez-Bailón et al. (2007) used the term 'double AGN,' a term which we had not included in our original search; the only reason we were able to include this pair was because Guainazzi et al. (2005) cited the discovery in the text of their own dual AGN discovery paper. As another example, several systematic searches for binary SMBHs in the years 2010-2013 were not found after our initial searches, as the authors of those studies had used different permutations of the phrase 'binary supermassive black hole.'

[2] as far as this author knows.

The reader can begin to see the picture we are painting: it is likely that our literature search is *still not complete*, as it is quite difficult to identify all cases of binary quasars, dual AGNs, binary SMBHs, and recoil candidates when authors use so many similar but *distinguishable* aliases. Clearly these issues of confusing and non-uniform nomenclature suggests the need for *common* and *physically motivated* nomenclature for these object classes. While it is, of course, perfectly fine for authors to use various permutations of one class label throughout their manuscript, the *commonly adopted* nomenclature should be used *at least once* so that that manuscript can be recovered in a single ADS search. An 'authoritative' nomenclature is beyond the scope of this report, as it requires careful discussions with many experts within each specific field in order to improve rather than confuse current and future scientific efforts. However, it is the opinion of this author that we should define a uniform, physically-motivated nomenclature which takes into account (1) projected separation, (2) velocity difference, and (3) luminosity regime.

4. NEXT STEPS

The next step for WMAGN is to follow-up on any remaining literature articles from 1970-2009 not yet included in this data release as well as push forward into the 2010-2020 decade. A 'system type' confidence flag has not yet been implemented, but that will be implemented before the next data release and will signify the confidence with which we have in the system classifications for any one entry in the catalog. As mentioned above, we will also work to correct for the next release any issues dealing with missing redshifts, missing brightness values, and proper selection and confirmation method information for each target. One important step which should be made in the future is the inclusion of more uniform brightness measurements; at the moment, we use the brightness measurements listed in the various catalogs or papers, and in many cases we use the V, B, R, or I band magnitudes listed on Simbad. Future releases would benefit from more uniform brightness measurements drawn from a more uniform database. Brightness measurements across multiple bands would also be useful to include. Finally, the next data release will employ a newly developed, physically-motivated nomenclature for these object classes.

5. APPENDIX

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Table 2. Multi-AGN Nomenclature Used in the Literature

Binary Quasars	Dual AGNs	Binary SMBHs & Recoiling SMBHs
Quasar pair	Binary AGN(s)	Binary SMBH(s)
Pairs of quasars	AGN Binary(ies)	SMBH pair(s)
Binary quasars	Dual Active Galactic Nuclei	SMBH Binary
Binary quasar	Dual Active Galactic Nucleus	SMBH Binaries
Quasar binary	Dual AGN(s)	Binary Supermassive Black Hole(s)
Quasar binaries	Double AGN(s)	Supermassive Binary Black Hole(s)
Dual quasar	Two Active Nuclei	Supermassive Black Hole Binary
Dual quasars	Two AGN(s)	Supermassive Black Hole Binaries
Double quasars	Dual Supermassive Black Holes	SBHB(s)
Double quasar	Dual SMBH(s)	Massive Black Hole Binary
Pairs of QSOs		Massive Black Hole Binaries
QSO pairs		Recoiling Supermassive Black Hole
Binary QSO		Recoiling SMBH
Binary QSOs		Recoiling Black Holes
		Recoiling AGN(s)

Note—**Aliases for Binary Quasars, Dual AGNs, Binary SMBHs, and Recoiling SMBHs in the Literature**. While likely not complete, we list here all aliases discovered for each class of object included in WMAGN DR 0.1. The four classes of objects make up the columns of this table.