A Uniformly Selected, Southern-sky 6dF, Optical AGN Catalog

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Abstract

We have constructed a catalog of active galactic nuclei (AGNs) with z < 0.13, based on optical spectroscopy, from the parent sample of galaxies in the Six-Degree Field (6dF) galaxy survey (Final Release of 6dFGS), a census of the Southern Hemisphere. This work is an extension of our all-sky AGN catalog in Zaw et al. (ZCF, hereafter). The ZCF is based on 43,533 galaxies with Ks ≤ 11.75 (z ≤ 0.09) in the Two Micron All-Sky Survey (2MASS) Redshift Survey (2MRS). The parent catalog of this work, the 6dF catalog, consists of 136,304 publicly available digital spectra for 125,071 galaxies with decl. ≤ 0° and Ks ≤ 12.65 (median z = 0.053). Our AGN catalog consists of 3109 broadline AGNs and 12,156 narrowline AGNs which satisfy the 2003 criteria, of which 3865 also satisfy the 2001 criteria. We also provide emission-line widths, fluxes, flux errors, and signal-to-noise ratios of all the galaxies in our spectroscopic sample, allowing users to customize the selection criteria. In addition, we provide the AGN likelihood for the rest of galaxies based on the availability and quality of their spectra. These likelihood values can be used for rigorous statistical analyses.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Galaxies (573); Catalogs (205); Emission line galaxies (459); AGN host galaxies (2017)

Supporting material: machine-readable tables

1. Introduction

A complete census of active galactic nuclei (AGNs) is important for understanding the growth of supermassive black holes (SMBHs) and the co-evolution of SMBHs and their host galaxies via AGN feedback. While deep surveys have the highest number of AGNs, nearby, all-sky catalogs are important for understanding the low-redshift universe. AGN catalogs can be used to search for and study AGN-related phenomena, such as circumnuclear water maser emission (e.g., Zhu et al. 2011) and ultra-high-energy cosmic rays (UHECRs; e.g., Pierre Auger Collaboration et al. 2007, 2010). The interpretation of statistical correlation studies between the arrival direction of UHECRs and the sky locations of AGNs depends on the completeness, homogeneity, and purity of the AGN catalogs used. Furthermore, nearby AGNs can be studied in greater detail and newly identified AGNs can serve as additional targets for high-angular-resolution studies, especially for powerful telescopes in the Southern Hemisphere such as the Atacama Large Millimeter/submillimeter Array (ALMA; Kurz et al. 2002), Multi AperTure mid-Infrared Spectroscopic Experiment (MATISSE; Lopez et al. 2014), and GRAVITY (Gravity Collaboration et al. 2017).

Analysis of optical emission lines is one of the most robust methods of identifying AGNs, either via the presence of a broad Balmer line for Type 1 (unobscured) AGNs or via the ratios of the fluxes of the forbidden lines to those of Balmer lines for Type 2 (obscured) AGNs. Optical lines also provide measurements of AGN activity, since the [O III] luminosity is a proxy for AGN bolometric luminosity, and of AGN obscuration, since the ratio of the Hα-to-Hβ line fluxes, called the Balmer decrement, increases with obscuration. Comparisons of the AGNs identified via different wavelengths is necessary to further assess the strengths and weaknesses of each method as well as a better understanding of the physical mechanisms responsible for the differences (e.g., Hickox & Alexander 2018). While optical observations of AGNs are highly reliable, due to their rich line information, they often miss low-luminosity and obscured AGNs. In comparison, infrared observations offer low obscuration bias but may miss star-formation-dominated AGNs and dust-poor AGNs. Similar to optical, X-ray observations are highly reliable and have low host contamination and low obscuration bias. However, X-ray observations can also miss low-luminosity and heavily obscured AGNs. If the AGN has no host contamination, and sufficient radio AGN emission, then the radio wavelength band should be ideal for obscuration bias-free analysis. However, only a small fraction of AGNs are radio-loud. AGNs identified with different methods should be combined to get a complete sample or as close as possible (e.g., Asmus et al. 2020). Our catalog can contribute to these studies, especially when compared with AGN catalogs from future X-ray telescopes, such as eROSITA,3 Athena,5 and the X-Ray Imaging and Spectroscopy Mission, formerly known as XARM,6 and far-infrared (far-IR) radio surveys such as ALMA7 and the Origins Space Telescope.8

We have identified AGNs, using optical line ratios, from the Final Release of the Six-Degree Field (6dF) Galaxy Survey (6dFGS; Jones et al. 2004, 2009), a census of nearby galaxies in the Southern Hemisphere with decl. < 0° and Ks < 12.65. This work is an extension of the Zaw et al. (2019; ZCF, hereafter)
all-sky, optical AGN catalog identified from the parent sample of Two Micron All-Sky Survey (2MASS) Redshift Survey (2MRS; Huchra et al. 2012) galaxy catalog, which contains 6dF galaxies with $K_s \leq 11.75$. The Final Release of 6dFGS sample consists of 136,304 spectra (125,071 galaxies), more than 10 times larger than the subset of 11,762 galaxies included in 2MRS.

This paper is organized as follows. Section 2 describes our spectroscopic sample. Section 3 describes the methods we used to isolate the emission lines and identify AGNs. Section 4 describes our AGN catalog. We present the impact of the spectral signal-to-noise ratio ($S/N$) on AGN detection rates and statistically correct for the resulting incompleteness and inhomogeneity of AGN detection rates in Section 5. In Section 6 we summarize our catalog and findings.

2. Spectroscopic Sample of Galaxies

We take 6dFGS (Jones et al. 2004, 2009) as the parent sample for constructing our southern sky optical AGN catalog. The survey targeted galaxies in the Southern Hemisphere (decl. $\leq 0^\circ$) with $K_s \leq 12.65$ (median $z = 0.053$) are from the 2MASS (Skrutskie et al. 2006) catalog. The 6dFGS catalog consists of 136,304 publicly available digital spectra of 125,071 galaxies taken with the 6dF multi-fiber spectrograph, operated on the United Kingdom Schmidt Telescope (UKST). Figure 1 shows the sky distribution of the galaxies in the 6dFGS. The Galactic latitude cut of the 6dF data is $|b| > 10^\circ$, as described by Jones et al. (2004), and the same is used for this work. The observations of 6dFGS were carried out at the UKST from 2001 to 2006 (Jones et al. 2004). The majority of the observations of the 6dFGS galaxies consist of two spectra, in the $V$ band and the $R$ band. Due to different gratings, data taken prior to 2002 October have a $V$ band spanning 4000–5600 Å and an $R$ band spanning 5500–8400 Å; later observations (≈80%) have a $V$ band spanning 3900–5600 Å and an $R$ band spanning 5300–7500 Å. $V$-band spectra have a resolution of 5–6 Å in FWHM, and $R$-band spectra have a resolution of 9–12 Å FWHM. The data do not have absolute flux calibration.

In order to run the optical spectroscopic analysis for AGN candidates, we need spectra in both the $V$ band, which covers the H$\beta$ and [O III] lines, and the $R$ band, which covers the H$\alpha$ and [N II] lines. There are $\sim$3460 spectra with only one (either $V$ or $R$) band available. Moreover, we find that there are $\sim$3400 spectra with negative mean $S/N$ in either the $V$ or $R$ band. We remove the spectra that only have one band available and the ones with a negative mean $S/N$ before we combine the $V$- and $R$-band data. To exclude the low $S/N$ cases of the absorption lines, we made a conservative cut at a mean $S/N \geq 3$ at both the $V$ and $R$ band, where the $S/N$ is defined as the mean $S/N$ over the full $V$ band or $R$ band. The data that passed the above criteria were then stitched to combine their $V$ and $R$ bands. We note that there are some galaxies with repeated observations—less than 10% of the total number of galaxies. A majority of these have two observations and a few have up to four observations. In case of repeated observations for the same galaxies ($\sim$9000 galaxies), we keep the spectra with the highest $S/N$. After the above selection, we have 101,263 galaxies whose spectra passed the data quality control.9

Note that a subset of the 6dF data (11,762 galaxies) were part of 2MRS (Huchra et al. 2012) and the AGNs in that sample are part of our all-sky optical AGN catalog (Zaw et al. 2019; ZCF). We do not repeat the data reduction and analysis of those here. The subset of 6dF data in 2MRS (hereafter 2MRS–6dF) and ZCF has a brighter magnitude cut at $K_s \leq 11.75$ to match the uniform sky distribution based on the 2MRS survey. Therefore, the $S/N$ of those spectra are higher than the full 6dF sample, with a magnitude cut of $K_s \leq 12.65$. We show the redshift distribution in Figure 2, where the subset of 6dF from 2MRS is highlighted in dark gray. Redshifts ($z$) are from Jones et al. (2004, 2009). Due to the $K_s$ requirement of 2MRS compared to 6dF, the objects of 2MRS–6dF are, in general, brighter than the rest of the 6dF objects. We therefore separate the 6dF sample into 2MRS–6dF and faint 6dF subsamples. We show the mean $S/N$ distribution over all wavelengths in Figure 3. The 2MRS–6dF subsample has an overall higher $S/N$, with the mean $S/N$ peaked at 20, while the full 6dF has significantly lower $S/N$, peaked at 10. Since the $S/N$ values are wavelength dependent (e.g., Zaw et al. 2019), we show the mean and standard deviations of the

Figure 1. The sky distribution of the galaxies in the Final Release of the 6dF Galaxy Survey.

Figure 2. Redshift distributions of the full 6dF sample, 2MRS–6dF subsample (dark gray), and the faint 6dF subsample. To distinguish the different samples of the different sets of 6dF galaxies, we call the whole 6dF as full 6dF, the subset of 6dF in 2MRS as 2MRS–6dF, and the 6dF galaxies that are not in the 2MRS and are fainter are faint 6dF. Redshifts are adopted from Jones et al. (2004, 2009).

9 The merged spectra will be made available as a .tar file on request.
S/N for the 6dF sample at various (continuum) wavelengths in Figure 4, where subsamples from 2MRS and the faint 6dF are presented to show the S/N differences.

We use the wavelength range covered by both the V and R bands (5500–5600 Å or 5300–5600 Å) to merge the 6dF data that satisfy the S/N criteria into a single spectrum for each galaxy. Data are evenly resampled to log space to reduce the possible pixel shifts between different bands since there are some small wavelength shifts for the same spectral features in between the two arms due to the wavelength calibration procedure. We then use the arm with higher resolution, namely the V band, as a template to fit for the overlapped wavelength ranges in the R band using the penalized pixel-fitting (pPXF; Cappellari & Emsellem 2004) method to determine the number of pixels to be shifted and to merge the bands. Note that this is an automatic procedure, which stitches most of the data successfully. There are cases where the automatic stitching process fails due to poor data quality in one of the arms, or a large number of pixels in the overlap region whose values are zero, especially for pixels at the beginning of the R band and end of the V band. Examples of arm-merged 6dF spectra with different continuum S/Ns are shown in Figure 5. We identified ~7000 spectra which fail automatic stitching by visual inspection. For these cases, we had to merge the data manually, i.e., scaling the arms and shifting the pixels until no obvious discontinuity appeared between the two bands.

We note that the spectra are not corrected for Earth’s atmospheric absorption, i.e., the telluric absorption. The B band around 6860–6890 Å overlaps with the optical AGN identification emission lines, [N II]–Hα complex, and can cause inaccurate line fluxes. This typically happens to the objects in the redshift range of 0.0407 < z < 0.05111. In those cases, we exclude these galaxies (~14%) from our sample. However, when a clear broad Hα component is present, we still keep the galaxy as a potential AGN candidate although the fluxes of the broad Hα in these galaxies cannot be measured accurately due to the telluric contamination. In addition, when the galaxies are at higher redshifts, z > 0.1428, the Hα line may shift out of the wavelength range, and we cannot assess whether or not they are AGNs.

3. Spectral Fitting and AGN Identification

The spectral fitting is performed on the bands-merged spectra in order to isolate the emission lines used in optical AGN identification. The spectral fitting procedure and validation are described in detail by Zaw et al. (2019). We briefly summarize it here.

3.1. Subtraction of the Host Galaxy Contribution to the Spectra

We subtract the stellar absorption and continuum emission from the galaxy by modeling them using full spectrum fitting with a stellar population model. As various of stellar population models are available, using different template models may result in systematic differences in AGN identification (Chen et al. 2018). The Vazdekis et al. (2010) stellar population models are based on the empirical stellar library MILES10 that populates the current largest stellar parameter space. Therefore, we use the Vazdekis et al. (2010) stellar population models, which cover the wavelength range from 3525 to 7500 Å. The model spectra have a resolution of FHWM 2.5 Å. We broaden the model spectra to match the observed spectral resolution of the 6dF data. Each 6dF spectrum is fit as a linear combination of the single stellar population (SSP) models using the pPXF (Cappellari & Emsellem 2004) program. We use the redshifts from Jones et al. (2004, 2009) as initial guesses in our SSP fits and refit for the recession velocity of each galaxy. The results we derived are consistent with the velocity from Jones et al. (2004, 2009). The mean value of the velocity difference distribution is 26 km s⁻¹ and the standard deviation of the velocity difference distribution is 79 km s⁻¹, roughly half the spectral resolution (150 km s⁻¹) of 6dF spectra. We applied same SSP χ² cut at 6.05 to keep 99% of the successful fits as in Zaw et al. (2019).

Due to the data quality or extremely strong emission features, about ~19% of galaxies failed in the template fitting procedure. A failed fit either has no template or yields an

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10 http://miles.iac.es/
over-broadened best-fit template (with Gaussian kernel broadening larger than 1000 km s$^{-1}$). In these cases, we fit for the continuum in the wavelengths on either side of the emission lines of interest and interpolate; no H$\alpha$ and H$\beta$ stellar absorption contributions are subtracted. If the failure is due to the fact that there is no significant absorption along the wavelength, then no bias is introduced. If the failure is due to low quality of the spectra, i.e., low S/N, the emissions of H$\alpha$

Figure 5. Sample spectra of the 6dF data. Left column shows spectra of emission-line galaxies, right column shows spectra of non-emission-line galaxies. Mean S/N increases from top to bottom.
and Hβ are underestimated, hence the line ratios are overestimated. This may lead to a systematically higher number of galaxies identified as AGNs (Zaw et al. 2019). We mark the AGNs that are identified after this local fitting procedure in the catalog. Readers should treat these objects with caution.

### 3.2. AGN Identification

After subtracting the continuum and absorption contributions from the host galaxy, we identify AGNs from the emission lines in the spectrum. Type 1 (broadline) AGNs are characterized by the presence of broadened hydrogen Balmer lines. As explained by the unified model (e.g., Antonucci 1993; Urry & Padovani 1995) this is the case when an AGN is unobscured, i.e., viewed face-on, and the Doppler broadened emission of the rapidly orbiting gas close to the supermassive black hole can be seen in the spectrum. If an AGN is seen closer to edge-on, the broadline regions are obscured by intervening gas and dust, leaving only narrow emission lines in the spectrum. In this case, the Type 2 (narrow line) AGNs can be identified from the flux ratios of the forbidden ([N II] and [O III]) lines to the Balmer (Hα and Hβ) lines.

We fit Gaussians to the emission lines in the spectrum and calculate the FWHM and the flux of each line. For the [N II]-Hα complex where the lines are blended together, three or four Gaussians are used to fit for the emission components simultaneously. The corresponding Gaussian components are used to calculate the fluxes and FWHM of [N II] and Hα lines. The details of the fitting procedure are described in Section 3.3 and are shown in Figure 6 of Zaw et al. (2019). Line fluxes are calculated under the Gaussian profiles in the wavelength bins within 3σ of the fitted peak, where σ is the fitted width of the Gaussian. Flux errors are calculated by adding in quadrature the value of each bin within the same wavelength range (i.e., 3σ) in the error spectrum.

Our method has been validated by comparing it with the results from Sloan Digital Sky Survey (SDSS) Data Release 8 (DR8; Aihara et al. 2011). The detailed description can be found in Zaw et al. (2019) and we briefly summarize the main procedures and results here. We first compared the fluxes and flux errors we derived for the SDSS galaxies in 2MRS with those from DR8 and found good agreement. We then compared our measurements for the galaxies that have spectra from both SDSS and 6dF. Since 6dF spectra do not have absolute flux calibration, we cannot compare the fluxes. However, we find that the flux ratios are consistent between SDSS and 6dF spectra for the same galaxies. Since 6dF spectra have lower S/N on average, requiring S/N ≥ 2.0 for the emission lines in 6dF spectra gives roughly the same AGN identification rates as requiring S/N ≥ 3.0 for the emission lines in SDSS spectra.

Because redder diagnostic lines such as [S II] λ6717, 6731 lines may shift out of the available spectral wavelength at high redshift (z ≥ 0.114), for completeness, we only use the bluer optical emission lines, i.e., broad and narrow Hα, narrow Hβ, [O III] λ5007, and [N II] λ6584, for AGN identification. We use the ratio between the flux and flux error, (S/N)_line, to evaluate the significance of the emission-line features. Following the detailed discussion in Zaw et al. (2019), where common galaxies with high S/N are available from SDSS, (S/N)_line ≥ 2.0 is used to further investigate the AGN candidates. An emission-line galaxy is defined as one having all four lines with (S/N)_line ≥ 2.0. When broad Hα has (S/N)_line < 2.0 while the other narrow lines all have (S/N)_line ≥ 2.0, a triple Gaussian is used to refit the [N II]-Hα complex to derive the corresponding line fluxes and flux errors. Galaxies with significant ([S II]/Hα ≥ 2.0) broad Hα components and having wide FWHM ≥ 1000 km s⁻¹ (e.g., Eun et al. 2017; Ho et al. 1997; Schneider et al. 2010; Stern & Laor 2012; Vanden Berk et al. 2006) are classified as Type 1 AGNs. As mentioned above, the [N II]-Hα complex is contaminated by the telluric absorptions at certain redshifts. The telluric-contaminated galaxies can be potential Type 1 AGNs. When such a galaxy shows a wide enough and prominent (usually through visual identification) broad Hα we still identify it as a Type 1 AGN, although its broad Hα flux is underestimated. Normally Hβ lines are weaker than Hα lines, therefore we do not require broad components of Hβ lines as the indication of Type 1 AGNs. However, there are potential Type 1 AGNs with broad Hβ components but weaker broad Hα as well. Those (about a few hundred) are semi-manually identified by checking their FWHM, (S/N)_line, and visual inspection. As mentioned in Section 2, no flux calibration was performed on the data, therefore, the absolute flux values are not available in this work.

When no significant broad Hα or Hβ are present, we use the line flux ratio as first proposed by Baldwin et al. (1981), known as the Baldwin–Phillips–Telesch (BPT) diagram to distinguish the Type 2 (narrow line) AGN from the star-forming galaxies whose spectra also show emission features from [O III], [N II], Hα, and Hβ. Line ratios [N II]/Hα and [O III]/Hβ are used in the BPT diagram to identify the possible AGN candidates. We adopt the two demarcation lines, which are usually used to separate AGNs and star-forming galaxies, namely,

$$\log([\text{O III}]/\text{Hβ}) > 0.61/\log([\text{N II}]/\text{Hα}) - 0.47 + 1.19$$

$$\log([\text{O III}]/\text{Hβ}) > 0.61/\log([\text{N II}]/\text{Hα}) - 0.05 + 1.3.$$  

The first is based on theoretical modeling of the maximal line ratios possible in star formation (Kewley et al. 2001), and the second is based on empirical studies of SDSS galaxies (Kauffmann et al. 2003). Galaxies with line ratios falling above the Kewley et al. (2001) line have forbidden line emission dominated by the AGN. Galaxies between the Kewley et al. (2001) and Kauffmann et al. (2003) lines are likely to be Type 2 AGN but can have contributions from both AGN and star formation galaxies. These galaxies are also referred as composite galaxies. We use the Kauffmann et al. (2003) line to identify AGNs for our catalog. If an AGN is also above the Kewley et al. (2001) line, we mark it as such.

As there are multiple AGN identification line ratios, such as [S II]/Hα and [O I]/Hα (Kewley et al. 2006) besides the main line ratio of [N II]/Hα, we explore the AGN identification consistency with different criteria for those galaxies whose [S II] and/or [O I] emission lines also have S/N ≥ 2.0. We show the results in Figures 6 and 7. In both plots, AGN identified from [N II]/Hα are marked as orange dots. The AGN identification using both [S II]/Hα and [O I]/Hα are in general agreement with the results of [N II]/Hα. As expected, some deviations occur from using different line ratios, with the shift of some galaxies being identified as AGNs to being identified as non-AGNs or vice versa. In general, only a small fraction of galaxies that were identified as AGNs by [N II]/Hα move into the non-AGN region when using [S II]/Hα and [O I]/Hα line ratios. A larger fraction of galaxies that are not AGNs by [N II]/Hα criteria are identified as AGNs in the [S II]/Hα and
[O I]/Hα BPT diagrams. This indicates that [N II]/Hα provides a purer sample of AGNs. In addition, [N II] lines are stronger and have lower wavelengths, i.e., they fall within the 6dF wavelength ranges at higher redshifts than the [S II] and [O I] lines. Therefore, we use [N II]/Hα as the AGN identification line ratio for this catalog.

4. The Catalog

Our AGN catalog consists of 3116 Type 1 AGNs and 12,162 Type 2 AGNs, which satisfy the Kauffmann et al. (2003) criteria. A subsample of 3866 Type 2 AGNs also satisfy the Kewley et al. (2001) criteria. We summarize the AGN numbers and fractions of each subsample in Table 1. N_sample is defined as the total number of valid spectra of each subsample, which includes the spectra that are free from telluric contaminations and some strong Type 1 AGN spectra affected by the telluric absorption. As mentioned above, we made a cut on S/N ≥ 3 in the V band for Type 2 AGNs and S/N ≥ 3 in the R band for Type 1 AGNs. A few Type 1 AGNs were identified by visual inspection whose R-band spectra are with an S/N ≤ 3 but strong broad emission lines. We mark the objects in common with Zaw et al. (2019) in this catalog by adopting their 2MRS name, i.e., name of 2MASS ID (TMID). Galaxies without TMID values are identified AGN from the faint 6dF sample. The sky distribution of our AGN catalog is shown in Figure 8. We show the BPT diagram for narrow emission-line galaxies in Figure 9, where line flux S/N cut (S/N)line ≥ 2.0 is applied to all four diagnostic lines. In Figure 10 we show the mean S/N of the AGN sample across the V band and R band as a function of redshift. Data quality quickly decreases with redshift, from a
Table 1
AGN Numbers and Fractions

| Type 1 | Type 2 K03 | Final Sample |
|--------|------------|--------------|
| 2MRS–6dF | 877 (8.46 ± 0.30%) | 2490 (24.01 ± 0.54%) | 10,370 |
| Faint 6dF | 2332 (3.03 ± 0.06%) | 9666 (12.56 ± 0.13%) | 76,953 |
| Full 6dF | 3109 (3.56 ± 0.06%) | 12,156 (13.92 ± 0.13%) | 87,323 |

Note. The table lists the number of AGNs in each subsample as well as the AGN fraction and error on the fraction, relative to the number of spectra in our final sample, for Type 1 (broadline), Type 2 (narrowline) according to the Kewley et al. (2001) (K01) criteria, and Type 2 according to the Kauffmann et al. (2003) (K03) criteria. The AGN fractions are not the same for the different subsamples due to the differences in S/ν, spectral resolution, and the spectral sampling of each subsample.

5. Type: AGN Type, T1 = Type 1, K01 = Type 2 satisfying Kewley et al. (2001) criteria, K03 = Type 2 satisfying Kauffmann et al. (2003) criteria;
6. SNR: S/ν of the V-arm of the spectrum which contains the Hβ line. Since Hβ is the weakest of the four AGN identification lines, this is the measure of spectral quality that affects the ability to detect narrow emission lines for Type 2 AGN identification;
7. SNR: S/ν of the R-arm of the spectrum which contains the Hα line, the measure of spectral quality that affects the ability to detect the broad Hα line for Type 1 AGN identification;
8. TMID: 2MASS ID, a combination of R.A. and decl. in sexagesimal units, to mark the objects in common with Zaw et al. (2019); and
9. SSP χ²: the reduced χ² from SSP fitting. We applied the same SSP χ² cut at 6.05 to keep 99% of the successful fits as in Zaw et al. (2019).

In the online version of our catalog, we provide extended information for the identified AGNs, namely the FWHM and flux of the broad Hα line, fluxes, and flux errors of the narrow lines used in AGN identification, and the (S/ν)line for each line. The additional information allows users to create their own customized AGN catalog using different AGN selection criteria. Note that the flux values are not absolute fluxes due to the un-flux-calibrated spectra. Therefore, the reported fluxes should only be used as ratios. AGNs with FWHM > 4000 km s⁻¹ in the broad Hα line are likely to have underestimated FWHM values, as their broad lines are often lumpy and asymmetric which need multiple Gaussians to properly model the line profiles (e.g., Greene & Ho 2007).

5. AGN Detection Rates

Statistical correlation studies are an important use of AGN catalogs. To fully understand the results of such studies, the completeness and homogeneity of the catalogs needs to be assessed. Our analysis in Zaw et al. (2019) shows that the AGN detection rates are due to the overall continuum S/ν of the spectrum. The line S/ν is determined by the spectral quality (i.e., the continuum S/ν) and the strength of the emission-line in a spectrum. The continuum S/ν is a measure of the noise at a given wavelength and the ability to detect a line at that wavelength. Since data quality plays a crucial role in spectroscopically identifying AGNs, the AGN fraction is accordingly affected.

As mentioned above, the 6dF data consist of two bands, namely the V band and the R band. The Hβ and [O III] lines are normally located in the V-band spectra and the Hα–[N II] lines are normally located in the R-band spectra. As the redshift of full 6dF
spans a larger range, it is more robust to monitor the mean \((S/N)_{\text{mean}}\) of each band rather than using a narrow range of spectra around the H\(\beta\) and H\(\alpha\) lines as we did in Zaw et al. (2019). The AGN detection rate as a function of continuum \(S/N\) is presented in Figure 12, where we also show the histograms of the \(S/N\) distributions. As seen in the left column, the AGN detection rates increase with \(S/N\) for both the full 6dF and the faint 6dF, until the rate flattens at a saturation value of \(S/N \sim 20–50\). The saturation \(S/N\) depends on the type of AGN. Type 1 AGNs have a saturation value of \(S/N \sim 40\), Type 2 AGNs that satisfy the Kewley et al. (2001) criteria have a saturation value of \(S/N \sim 50\), and Type 2 AGNs that satisfy the Kauffmann et al. (2003) criteria have a saturation value of \(S/N \sim 20\) in the faint 6dF. Type 2 AGN that satisfy the Kauffmann et al. (2003) criteria for the full 6dF sample follows a smooth increasing curve, which is dominated by the 2MRS galaxies, while a more complicated behavior is seen in the faint 6dF sample due to its lower \(S/N\). As mentioned above, the full 6dF has an overall lower \(S/N\) compared to the 2MRS subsample; a threshold is observed for the AGN fraction, namely \(S/N \sim 55\). This behavior is consistent among the 2MRS–6dF, faint 6dF, and full 6dF sample. In the right column, we show the \(S/N\) distributions of the subsamples. As mentioned before, the 2MRS–6dF subsample has higher \(S/N\) on average.

We show the AGN ratio across the sky (left panel) and its distribution as a function of redshift (right panel) in Figure 13. The inhomogeneity of the AGN detection rates is observed in both panels, which is strongly affected by the data quality. Data with lower redshifts \((z < 0.07)\) show higher AGN rates due to their higher data quality (as shown in Figure 12). While data with higher redshifts tend to flatten out at an AGN detection rate around 0.15. The gap in redshift panel \(z\) shows unavailable data due to telluric absorption, the same effect is seen in Figure 10.

Figure 9. The BPT diagrams for the emission-line galaxies \((S/N)_{\text{mean}} \geq 2.0\) for all four lines. 6dF galaxies in 2MRS are shown as orange dots for comparison. The green and red lines denote the Kauffmann et al. (2003) and Kewley et al. (2001) criteria for narrow line AGNs, respectively.

Figure 10. Mean \(S/N\) of the AGN sample as a function of redshift. The mean value in each redshift bin is shown as a square. Error bars are the standard deviations of each bin.
Figure 11. The Type 2 AGNs in our catalog, separated into Seyferts (purple) and LINERS (green) using the Kewley et al. (2006) criteria. There are more LINERs than Seyferts in the 2MRS–6dF subsample (K_s < 11.75), and more Seyferts than LINERS in the faint 6dF subsample (K_s < 12.65) due to the lower data quality. LINERs have weaker emission lines, so they are preferentially lost when spectral S/N decreases, i.e., the faint 6dF galaxies. Note that we use the [O III]/Hβ vs. [N II]/Hα BPT diagram to identify AGNs, so some emission-line galaxies that do not qualify as AGNs in the main diagram appear in the AGN region in the [O III]/Hβ vs. [S II]/Hα diagram.

Table 2
The AGN Catalog (Illustrative Extract)

| TARGETNAME | R.A. (deg) | Decl. (deg) | z   | Type | SN_V | SN_K | TMID   | SSP χ² |
|------------|-----------|-------------|-----|------|------|------|--------|--------|
| g0000113_050932 | 0.04709   | −5.15876    | 0.019057 | K03 | 12.6 | 9.6 | 0000113-050931 | 1.26 |
| g0000182_479223 | 0.07596   | −47.48958   | 0.027322 | K01  | 23.6 | 23.6 | 00001825-479226 | 0.99 |
| g0000261_490431 | 0.10858   | −49.07539   | 0.067518 | K01, Sy2 | 12.8 | 12.0 | 00000356-014547 | 1.56 |
| g0000356_014547 | 0.14849   | −1.76318    | 0.024424 | K03  | 19.9 | 17.9 | 00001137-440046 | 0.92 |
| g0001138_440043 | 0.30740   | −44.01183   | 0.038964 | K03  | 17.1 | 15.5 | 00001137-440046 | 0.92 |
| g0001361_144455 | 0.40020   | −14.74867   | 0.037679 | K01, LINER | 21.5 | 28.8 | 00013605-144454 | 1.14 |
| g0001558_273738 | 0.48258   | −27.62723   | 0.028330 | K01  | 14.1 | 17.8 | 00015583-237382 | 2.07 |
| g0002039_323802 | 0.51617   | −33.46728   | 0.028937 | K03  | 33.4 | 32.6 | 00020386-332803 | 1.37 |
| g0002348_034239 | 0.64505   | −3.71072    | 0.021498 | Sy1  | 21.4 | 16.6 | 00023480-034238 | 1.84 |
| g0004323_404258 | 13.63458  | −40.71603   | 0.024142 | K03  | 26.7 | 27.3 | 00543231-404257 | 0.62 |
| g1211143_393327 | 182.80946 | −39.55747   | 0.061064 | Sy1  | 17.3 | 18.8 | 12111425-393328 | 0.77 |
| g1669162_291654 | 241.56742 | −29.28167   | 0.015668 | K03  | 68.1 | 71.9 | 472923158-237382 | 4.72 |
| g1901287_243406 | 285.36954 | −24.56833   | 0.029157 | Sy1  | 27.1 | 28.5 | 19012871-243406 | 1.41 |
| g1955064_392224 | 298.77538 | −39.37258   | 0.019925 | K01  | 52.7 | 52.3 | 40425781-404257 | 4.06 |
| g2124243_234134 | 321.10283 | −23.69403   | 0.000307 | Sy1  | 5.1  | 10.9 | 22415822-373442 | 0.79 |
| g2241589_373443 | 340.49258 | −37.57853   | 0.028797 | K01  | 23.3 | 24.5 | 22415822-373442 | 0.79 |
| g2312198_274019 | 348.08262 | −27.67189   | 0.004918 | K01  | 3.8  | 3.7  | 23121982-274019 | 0.78 |
| g2347461_372925 | 356.92421 | −37.49031   | 0.043774 | Sy1  | 22.9 | 25.9 | 23121982-274019 | 0.72 |
| g148026_184952  | 177.01100 | −18.83114   | 0.033478 | Sy1  | 3.8  | 3.9  | 148026184952 | 3.19 |
| g1526535_310839 | 231.72292 | −31.14408   | 0.047590 | Sy1  | 17.1 | 19.7 | 1526535-310839 | 1.07 |

Note. TARGETNAME: 6dF ID, # indicates that local fitting was used to estimate the galaxy contribution; * indicates Type 1 AGNs identified from broad Hβ; t indicates the Type 1 AGNs may be contaminated by telluric absorption in the [N II]–Hα complex; R.A.: R.A.; decl.: decl.; z: redshift; and Type: AGN type, Sy1 = Type 1, K01 = Type 2 with Kewley et al. (2001) criteria, K03 = Type 2 with Kauffmann et al. (2003) criteria. We use [S II] to classify the LINERs and Type 2 Seyferts (Sy2) by adopting Kewley et al. (2006) criteria. When [S II] falls within the 6dF wavelength range, a K01 galaxy that satisfies either the LINERs or Sy2 criteria is marked accordingly in the column “Type”; TMID: 2MASS ID, indicate common AGNs in Zaw et al. (2019); SSP χ²: reduced χ² from the SSP fitting. The full table also includes the emission-line widths, fluxes, and flux errors of all the AGNs in the catalog.

(This table is available in its entirety in machine-readable form.)

In order to be used in a rigorous statistical analysis, e.g., for correlations with the arrival direction of cosmic rays, we need to address the detailed inhomogeneity and incompleteness due to the missing or telluric-contaminated spectra. We perform similar corrections as in Zaw et al. (2019). We fit the AGN fraction as a function of the continuum S/N using a linear correlation below the saturation S/N value, and a constant above, for Type 1 AGNs and Type 2 AGNs satisfying the Kewley et al. (2001) criteria.11 Here are the relations we obtain above. The AGN fraction for Type 2 AGNs satisfying the Kauffmann et al. (2003) criteria seem to follow a curve rather than a line and requires a more complicated analysis.

We use the Kewley et al. (2001) criteria in this analysis because they yield a purer sample of galaxies with AGN activity. Furthermore, the AGN fraction for Type 2 AGNs satisfying the Kauffmann et al. (2003) criteria seem to follow a curve rather than a line and requires a more complicated analysis.

11

Illustrative Extract

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Figure 12. AGN fraction (left column) and distribution (right column) as a function of the continuum S/N. The S/N of R-band spectra is assessed for Type 1 AGNs and the S/N of V-band spectra is assessed for Type 2 AGNs. The top row is for Type 1 AGNs, the middle row is for Type 2 AGNs satisfying the Kewley et al. (2001) criteria, and the bottom row is for Type 2 AGNs satisfying the Kauffmann et al. (2003) criteria. The AGN fraction increases with S/N and saturates at S/N $\gtrsim 40$; beyond this value, the AGN fractions for the different subsamples are consistent with each other.

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from the fits:

$$R_{fT1} = (SN1) \times 0.00261 - 0.00128 \text{ for } SN1 < 40$$
$$= 0.108 \equiv R_{fT1} \text{ for } SN1 \geq 40,$$

$$R_{fT2} = (SN2) \times 0.00346 - 0.00184 \text{ for } SN2 < 55$$
$$= 0.192 \equiv R_{fT2} \text{ for } SN2 \geq 55,$$

where SN1 (SN2) is the continuum S/N for the R-band arm (V-band arm), i.e., containing the H$\alpha$ (H$\beta$) line; $R_{fT1}$ ($R_{fT2}$) is
the AGN fraction for the given galaxy’s S/N value for Type 1 (Type 2) AGNs; and $R_{T1}$ ($R_{T2}$) is the saturation value for the Type 1 (Type 2) AGN fraction. We assign a Type 1 AGN likelihood of zero for a non-AGN whose S/N (R-band arm) value is above 40. Similarly, we assign a Type 2 AGN likelihood of zero for a non-AGN whose S/N (V-band arm) is above 55. For galaxies with S/N values in the R-band and V-band arm less than the saturation values, we assign likelihoods as follows:

$$L_{T1} = \frac{R_{T1} - R_{T1}^0}{1 - R_{T1} - R_{T2}^0}$$

(5)

$$L_{T2} = \frac{R_{T2} - R_{T2}^0}{1 - R_{T1} - R_{T2}^0},$$

(6)

where $L_{T1}$ and $L_{T2}$ are the likelihoods for the galaxy to be a Type 1 and Type 2 AGN, respectively. We assign the saturation AGN fractions as their AGN likelihoods for galaxies that are not in our spectroscopic sample. The probability for a galaxy to be an AGN is the sum of the likelihoods for Type 1 and Type 2 AGNs. In this work, those galaxies whose spectra contaminated by telluric features around the AGN diagnostic emission lines are not in our spectroscopic sample. We assign them a flat likelihood of 0.3005, the saturation value for Type 1 and Type 2 AGNs. The galaxies identified as AGNs are

Figure 13. Left panel: ratio of the number of identified AGNs to the number of galaxies in our spectroscopic sample ($N_{\text{sample}}$), across the southern sky. The sky has been divided into 768 equal-area regions, and the color indicates the AGN fraction. Right panel: 6dF AGN fraction as a function of redshift. In these plots, we have combined the broadline AGNs with the narrowline AGNs that satisfy the Kauffmann et al. (2003) criteria. The $N_{\text{sample}}$ includes the spectra free from telluric contamination and a few hundred spectra with strong broad Hα emission components that are affected by the telluric absorption.

Table 3
Non-AGN Galaxies (Illustrative Extract)

| TARGETNAME | R.A. (deg) | Decl. (deg) | z   | Type | TMID | SNV | SNx | PROB1 | PROB2 | PROBAGN |
|------------|-----------|------------|-----|------|------|-----|-----|-------|-------|---------|
| g2359411_051614 | 359.9212 | -5.27053 | 0.11729 | ...  | 6.0  | 10.2 | 0.0870 | 0.1811 | 0.2682 |
| g2359433_540227 | 359.93050 | -54.04086 | 0.084917 | ...  | 17.3 | 20.0 | 0.0646 | 0.1506 | 0.2152 |
| g2359470_750411 | 359.94952 | -75.06958 | 0.058782 | ...  | 7.9  | 7.0  | 0.0956 | 0.1740 | 0.2696 |
| g2359485_455710 | 359.95192 | -45.95289 | 0.065434 | ...  | 8.4  | 7.5  | 0.0944 | 0.1727 | 0.2672 |
| g2359500_205008 | 359.95829 | -20.83556 | 0.064346 | ...  | 9.2  | 9.0  | 0.0910 | 0.1710 | 0.2620 |
| g2359553_123752 | 359.98029 | -12.63114 | 0.104852 | ...  | 6.1  | 10.1 | 0.0872 | 0.1808 | 0.2680 |
| g2359592_691411 | 359.99675 | -69.23639 | 0.060147 | ...  | 5.2  | 7.0  | 0.0945 | 0.1820 | 0.2765 |
| g2359390_484804 | 359.91246 | -48.80111 | 0.065728 | E=Emi | 12.0 | 12.5 | 0.0831 | 0.1642 | 0.2473 |
| g2359437_290936 | 359.93229 | -29.15992 | 0.027535 | E=Emi | 9.2  | 9.6  | 0.0896 | 0.1712 | 0.2609 |
| g2359547_301207 | 359.97804 | -30.20192 | 0.030624 | ...  | 10.7 | 10.3 | 0.0882 | 0.1672 | 0.2554 |
| g2359555_392832 | 359.98104 | -39.47542 | 0.102470 | ...  | 10.0 | 15.9 | 0.0735 | 0.1719 | 0.2454 |
| g0000008_622266 | 0.03601 | -6.37399 | 0.021785 | E=Emi | 00000865-0622263 | 15.8 | 17.7 | 0.0705 | 0.1542 | 0.2247 |
| g0000023_470108 | 0.09836 | -47.01881 | 0.019984 | ...  | 00002363-4701076 | 23.0 | 10.3 | 0.0923 | 0.1277 | 0.2200 |
| g0000058_333643 | 0.24409 | -33.61195 | 0.023063 | E=Emi | 00005858-3336429 | 13.9 | 13.5 | 0.0810 | 0.1587 | 0.2397 |
| g0000109_431950 | 0.26204 | -43.33044 | 0.038783 | ...  | 000010289-4319496 | 21.6 | 24.0 | 0.0544 | 0.1378 | 0.1922 |
| g0000117_530035 | 0.32276 | -53.00967 | 0.032436 | E=Emi | 000011748-5300348 | 11.9 | 13.5 | 0.0804 | 0.1649 | 0.2453 |
| g0000130_072610 | 0.38729 | -7.43614 | 0.029474 | E=Emi | 000013295-0726099 | 24.8 | 25.1 | 0.0518 | 0.1271 | 0.1789 |

Note. TARGETNAME: 6dF ID; R.A.: R.A.; decl.: decl.; z: redshift; Type: galaxy type, "..." = non-emission-line galaxy, ‘Emi’=galaxy with emission lines; TMID: 2MASS ID, indicate common galaxies from 2MRS; PROB1: likelihood to be a Type 1 AGN, i.e., $L_{RR}^1$; PROB2: likelihood to be a Type 2 AGN satisfying the Kewley et al. (2001) criteria, i.e., $L_{RR}^2$; and PROBAGN: likelihood to be an AGN, sum of $L_{RR}^1$ and $L_{RR}^2$. The full table also includes the emission-line widths, fluxes, and flux errors of all the non-AGN in the catalog. (This table is available in its entirety in machine-readable form.)
assigned an AGN likelihood of 1.0. Examples of the likelihood assignments for the non-AGNs and galaxies with spectra contaminated by telluric absorption are given in Tables 3 and 4, respectively. These likelihoods can be used to statistically correct for both the inhomogeneity and incompleteness. These expressions for the likelihoods are only valid for the selection criteria used in this work, as specified in Sections 3.2 and 4. If the user chooses different criteria, e.g., different line S/N or BPT criteria, the homogeneity and completeness analyses should be repeated for the criteria used.

We show the likelihood corrected AGN distribution, using the above Equations (3)–(6), across the sky and redshift in Figure 14. The AGN rates are now homogeneously distributed.

We also explore the ratio of Type 1 (Sy1) to Type 2 (K01) AGN. The Type 1 to Type 2 AGN ratios vary widely across the sky and redshift as shown in Figure 15. This is expected since the Type 1 (Sy1) and Type 2 (K01) AGN fractions have different dependences on continuum S/N as seen in Figure 12. We correct the effect of the S/N in assigning AGN likelihood by using Equations (3)–(6) where the Type 1 and Type 2 AGN likelihoods are separately addressed. The statistical correction mostly eliminates the inhomogeneity in the Type 1/Type 2 ratio across the sky and in redshift, as shown in Figure 16.

This catalog, like other optical AGN catalogs, is affected by dust obscuration. The only indicator of reddening available to us is the Balmer decrement, Hα/Hβ, which has a nominal value of 3 for unobscured AGNs and increases with obscuration.

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**Table 4**

The 6dF Galaxies Affected by the Telluric Contamination (Illustrative Extract)

| TARGETNAME | R.A. (deg) | Decl. (deg) | z | TMID | PROB1 | PROB2 | PROBAGN |
|------------|-----------|------------|---|------|------|------|--------|
| g0000009_405412 | 0.00354 | −40.90330 | 0.049704 | 00000082-4054120 | 0.1084 | 0.1921 | 0.3005 |
| g0000190_441241 | 0.07900 | −44.21150 | 0.048703 | 0.1084 | 0.1921 | 0.3005 |
| g0000202_394843 | 0.08429 | −39.81197 | 0.042436 | 0.1084 | 0.1921 | 0.3005 |
| g0000251_260240 | 0.10454 | −26.04450 | 0.050845 | 00002509-2602401 | 0.1084 | 0.1921 | 0.3005 |
| g0000328_401323 | 0.13658 | −40.22929 | 0.043005 | 0.1084 | 0.1921 | 0.3005 |
| g0000358_403432 | 0.14896 | −40.57561 | 0.050031 | 0.1084 | 0.1921 | 0.3005 |
| g0000399_110927 | 0.16617 | −11.15750 | 0.045552 | 0.1084 | 0.1921 | 0.3005 |
| g0000444_032854 | 0.18496 | −3.48172 | 0.047255 | 0.1084 | 0.1921 | 0.3005 |
| g0000459_815803 | 0.19129 | −81.96742 | 0.042244 | 0.1084 | 0.1921 | 0.3005 |
| g0000495_253536 | 0.20629 | −25.89875 | 0.051068 | 0.1084 | 0.1921 | 0.3005 |
| g0000523_355037 | 0.21805 | −35.84368 | 0.051973 | 00005234-3550370 | 0.1084 | 0.1921 | 0.3005 |
| g0000532_355911 | 0.22161 | −35.98630 | 0.050041 | 00005317-3559104 | 0.1084 | 0.1921 | 0.3005 |
| g0000555_404245 | 0.23129 | −40.71239 | 0.049594 | 0.1084 | 0.1921 | 0.3005 |
| g0000558_255421 | 0.23238 | −25.90581 | 0.050463 | 0.1084 | 0.1921 | 0.3005 |
| g0001007_375430 | 0.25275 | −37.90836 | 0.050417 | 0.1084 | 0.1921 | 0.3005 |
| g0001080_534149 | 0.28342 | −53.69697 | 0.048467 | 0.1084 | 0.1921 | 0.3005 |
| g0001083_380735 | 0.28446 | −38.12636 | 0.045083 | 0.1084 | 0.1921 | 0.3005 |
| g0001094_384406 | 0.28908 | −38.73511 | 0.051017 | 0.1084 | 0.1921 | 0.3005 |
| g0001224_384521 | 0.34347 | −38.75589 | 0.051265 | 00012242-3845212 | 0.1084 | 0.1921 | 0.3005 |

Note. Due to the telluric contamination, these spectra are not usable for identifying AGN candidates. We therefore assigned the uniform AGN probability for these galaxies. TARGETNAME: 6dF ID; R.A.: R.A.; decl.: decl.; z: redshift; TMID: 2MASS ID, indicate common galaxies from 2MRS; PROB1: likelihood to be a Type 1 AGN; PROB2: likelihood to be a Type 2 AGN satisfying the Kewley et al. (2001) criteria; and PROBAGN: likelihood to be an AGN.

(This table is available in its entirety in machine-readable form.)
However, due to lack of absolute flux calibration, and Hα, Hβ located in two different arms, small values of Balmer decrements obtained from 6dF spectra are not reliable. Therefore, we cannot assess and correct for the inhomogeneity in this catalog due to dust obscuration.

6. Conclusions

We have constructed a southern-sky catalog of AGNs based on the optical spectroscopy of the 6dF galaxy survey. The catalog consists of 3109 broadline AGNs, and 12,156 narrow-line AGNs that satisfy the Kauffmann et al. (2003) criteria, of which 3865 also satisfy the Kewley et al. (2001) criteria. We report emission-line widths, fluxes, flux errors, and S/Ns for all the galaxies in our spectroscopic sample, allowing users to customize the selection criteria. We perform an assessment of the completeness and homogeneity of our catalog across the sky and in redshift. Due to the inhomogeneity in the S/N, the AGN fractions are not evenly distributed. Especially at higher redshift, data with lower S/N are dominating the sample, where the detection rates rapidly drop down. In order to minimize the effect of continuum S/N on Type 1 (Type 2) AGN detection efficiency, the minimum requirement for the continuum S/N for a 6dF spectrum should be \( \geq 55 \) in the \( R \) band (\( S/N \geq 40 \) in the \( V \) band).

We provided means to correct for the S/N oriented inhomogeneity in our AGN catalog. An AGN likelihood is assigned to the objects with low S/N and those whose diagnostic lines are contaminated by the telluric absorptions. After these corrections, the AGN fractions are uniform across the southern sky and in redshift, making the catalog suitable for rigorous statistical analysis.

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References
Aihara, H., Allende Prieto, C., An, D., et al. 2011, ApJS, 193, 29
Antonucci, R. 1993, ARA&A, 31, 473
Asmus, D., Greenwell, C. L., Gandhi, P., et al. 2020, MNRAS, 494, 1784
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138
Chen, Y.-P., Zaw, I., & Farrar, G. R. 2018, ApJ, 861, 67
Eun, D.-i., Woo, J.-H., & Bae, H.-J. 2017, ApJ, 842, 5
Gravity Collaboration, Abuter, R., Accardo, M., et al. 2017, A&A, 602A, 94
Greene, J. E., & Ho, L. C. 2007, ApJ, 667, 131
Hickox, R. C., & Alexander, D. M. 2018, ARA&A, 56, 625
Ho, L. C., Filippenko, A. V., Sargent, W. L. W., & Peng, C. Y. 1997, ApJS, 112, 391
Huchra, J. P., Macri, L. M., Masters, K. L., et al. 2012, ApJS, 199, 26
Jones, D. H., Read, M. A., Saunders, W., et al. 2009, MNRAS, 399, 683
Jones, D. H., Saunders, W., Colless, M., et al. 2004, MNRAS, 355, 747
Kauffmann, G., Heckman, T. M., Tremonti, C., et al. 2003, MNRAS, 346, 1055
Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., & Trevena, J. 2001, ApJ, 556, 121
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 964
Kurz, R., Guilloteau, S., & Shaver, P. 2002, Msngr, 107, 7
Lopez, B., Lagarde, S., Jaffe, W., et al. 2014, Msngr, 157, 5
Pierre Auger Collaboration, Abraham, J., Abreu, P., et al. 2007, Sci, 318, 938
Pierre Auger Collaboration, Abreu, P., Aglietta, M., et al. 2010, ApPh, 34, 314
Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 2360
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Stern, J., & Laor, A. 2012, MNRAS, 426, 2703
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Vanden Berk, D. E., Shen, J., Yip, C.-W., et al. 2006, AJ, 131, 84
Vazdeksis, A., Sánchez-Blázquez, P., Falcón-Barroso, J., et al. 2010, MNRAS, 404, 1639
Zaw, I., Chen, Y.-P., & Farrar, G. R. 2019, ApJ, 872, 134
Zhu, G., Zaw, I., Blanton, M. R., & Greenhill, L. J. 2011, ApJ, 742, 73