OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term*

A search for bright quasars at $3 < z < 6$

P.I.: Jan-Torge Schindler* (SO; *jtschindler@email.arizona.edu*;)

CoI(s): Xiaohui Fan (SO), Jinyi Yang (SO), Feige Wang (SO), Ian McGreer (SO)

Abstract of Scientific Justification

SDSS has been very successful in finding more than 160,000 quasars. This quasar sample allowed us to study the Black Hole mass growth by accretion and mergers, the co-evolution of super massive Black Holes with their host galaxies and the Intergalactic Medium (IGM) along the quasar sight lines. The selection of quasars in the SDSS sample was carried out only using optical colors. However, pure selection of quasars on their optical photometry is difficult since the stellar locus overlaps with the quasar population in this color space. Bright quasars with redshifts of $z = 3 - 6$ are not only important to populate the black hole mass function and the quasar luminosity function, two important statistics to study quasar and black hole evolution as a whole. They are also powerful tools to study the IGM in the era of reionization. We have developed a new quasar selection technique based on infrared photometry (WISE/2MASS) to identify quasars that have been missed before. We propose to continue our pilot survey, targeting bright quasars at redshifts of $z = 3 - 6$. For our observations we request 5 dark/gray nights on the BOK/BCSpec or the VATT/VATTSpec to carry out 30 pilot observations which are an important test for the long-term project. Furthermore we request 1 dark/grey nights on the MMT/Red Channel Spectrograph follow up interesting targets previously identified the VATT we propose for. If the pilot survey is successful we aim to build a catalog of bright quasars at this redshift regime over two times the area of SDSS using 2MASS and WISE with additional optical information of Pan-STARRS, DES, SDSS and DESI.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT		Red Channel Sp.			1	dark/gray	Oct–Dec	Oct–Dec	no	no
2	Bok		BCSpec			5	dark/gray	Oct–Dec	Oct–Dec	no	no
or:											
2a	VATT		VATTSpec			5	dark/gray	Oct–Dec	Oct–Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Since I will take my oral prelim in the middle of September 2015 I ask to not be scheduled around that time. We further ask the VATT run to be scheduled before the MMT run.

no text past this line

A * appended to the proposal type indicates a continuation proposal; a * appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a $*$ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	Quasar candidates	20h-4h	-10 to +50	$z_{\rm AB} < 19$

Approval for Instrument Use from PI: N/A

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Jan-Torge Schindler	Xiaohui Fan		no	yes

Scientific Justification

Quasars at higher redshifts are important tools to learn about the co-evolution of galaxies and black hole growth. A recent publication by Trakhtenbrot et al. (2011) suggests that $z \sim 5$ quasars have higher accretion rates than those observed at lower redshifts. According to the authors these quasars are the progenitors for the most massive black holes observed at intermediate redshifts ($z \simeq 2.4$, $z \simeq 3.3$). To investigate these findings and further study the mass growth of the most massive objects a larger sample of bright quasars at redshifts of $3 < z < 6$ is necessary.

The quasar luminosity function is an important statistic in the study of quasar evolution and there have been numerous calculations of it at various redshifts (at z $<$ 2.2 (Fan et al. 2001;Croom et al. 2009) ,at 2.2 $<$ z $<$ 3.5 (Ross et al. 2012; Palanque-Delabrouille et al. 2013), at $z \leq 4$ (La Franca et al. 2005), at 4.7 $<$ z $<$ 5.1 (McGreer et al. 2013),at z $\sim$ 6 (Jiang et al. 2009; Willott et al. 2010)). However the redshift range between $5.2 < z < 5.7$ of the QLF has high uncertainties due to the limited sample size of $\sim$ 20 known quasars. This gap in the known redshift distribution of quasars stems from a degeneracy with late-type stars (M, L, T dwarfs) in the optical color selection. Especially the bright objects in this redshift range are missing. The most recent high redshift work of the QLF at $z \sim 5$ by McGreer et al (2013) only encompasses nine quasars in their sample that are brighter than i=20. This lack of luminous quasars in the QLF causes some uncertainties in its bright end slope.

Another important tool for understanding black hole mass accretion and growth or the co-evolution between supermassive black holes (SMBH) and their hosts is the black hole mass function (BHMF). Willott et al (2010) suggested that the evolution in the black hole mass function from $z = 6$ to $z = 0$ is of a factor of $\sim 10^4$. This is much larger than the $\sim 10^2$ increase in the stellar mass function over the same redshift interval. In combination with the local black hole to stellar mass relation (e.g. Haering et al. 2004) this evidence suggests that black holes grow very rapidly from $z = 6$ to $z = 0$. The previously mentioned publication of Trakhtenbrot et al. (2011, see Figure 1) argues that the first of such rapid growth phases happens around a redshift of $z \simeq 4.8$. To answer questions on when this growth phase begins and how black holes evolve a larger sample of quasars at this redshift range is needed.

In addition, observations of the Gunn-Peterson effect using absorption spectra of quasars at $z \gtrsim 5.7$ have established a redshift of $z \sim 6$ as the end of cosmic reionization, when the IGM is rapidly transforming from largely neutral to completely ionized (e.g. Fan et al. 2006). However, the detailed reionization history remains largely undetermined by current observation. The physical conditions of the IGM post reionization, at $z \sim 5 - 6$, provides the basic boundary conditions of models of reionization, such as the evolution of the IGM temperature, it's metallicity, the photon mean free path and the impact of helium reionization (e.g. Bolton et al 2012). All these measurable parameters place strong constraints on models of reionization topology as well as on the sources of reionization and chemical feedback by early galaxy population. However, the lack of known luminous quasars at $z \sim 5 - 5.7$ is a significant limiting factor to understanding this key era of reionization history.

A difficult problem with color selection of quasars in the optical is the overlap of the stellar main sequence with the quasar population, e.g. in ug-gr or gz-gr color diagrams using SDSS filters. Using infrared data in combination with optical colors, we have developed a method to discover quasars at intermediate redshifts up to $z \approx 5$ (Wu & Jia 2010; Wu et al. 2011,2012,2013). We built on this experience and devised a new method based entirely on infrared colors to solve the ambiguity of quasars and stars in optical color space.

We determine our primary candidate list from sources of the WISE ALLWISE catalog in combination with photometric data from the 2MASS PSC. Our candidates are selected using a JK-KW1 color cut (Fig. 1, left panels) that allows for a very clean separation between stars and galaxies/quasars. For a galactic latitude of $l > 30\,\mathrm{deg}$ we retrieve about 2.5 million sources. To distinguish between the galaxies and the stars we match our source list with only point sources of the SDSS DR12 catalog. As shown in Fig. 2 this allows us to reduce the number of candidates significantly and we receive a candidate list with about 23000 sources. Using a photometric redshift estimate, a brightness and a cleanness criterion, we prioritize on our source list. The cleanness criterion is a JK-KW2 color cut (see Fig. 1, right panels) which reduces the number of candidates that are most probably not stars to about 2858. In the last step of our selection process we

visually inspect each candidate and sort out sources that are blended in WISE.

Our improved color selection, using infrared colors and optical colors, will definitely identify new bright quasars in the SDSS footprint that have been missed with optical selection methods. The proposed observations on the VATT/BOK telescope are designed to identify new targets, while we aim to follow up interesting targets, found with the proposed VATT run, with the MMT.

The long term goal is to use our color selection criteria to build a catalog of bright quasars at $3 < z < 6$ over the entire sky. For this we will also use datasets from surveys like DES, DESI, SDSS, Pan-STARRS, 2MASS and WISE. Our goal is to track the population of the most active AGN and most massive black holes to study the merger and accretion history of these objects in great detail. Furthermore bright high-redshift quasars are the most important probes to study the IGM in the era of cosmic reionization. Our sample will populate the bright end of the quasar luminosity function and help to constrain the bright end slope from $3 < z < 6$.

References

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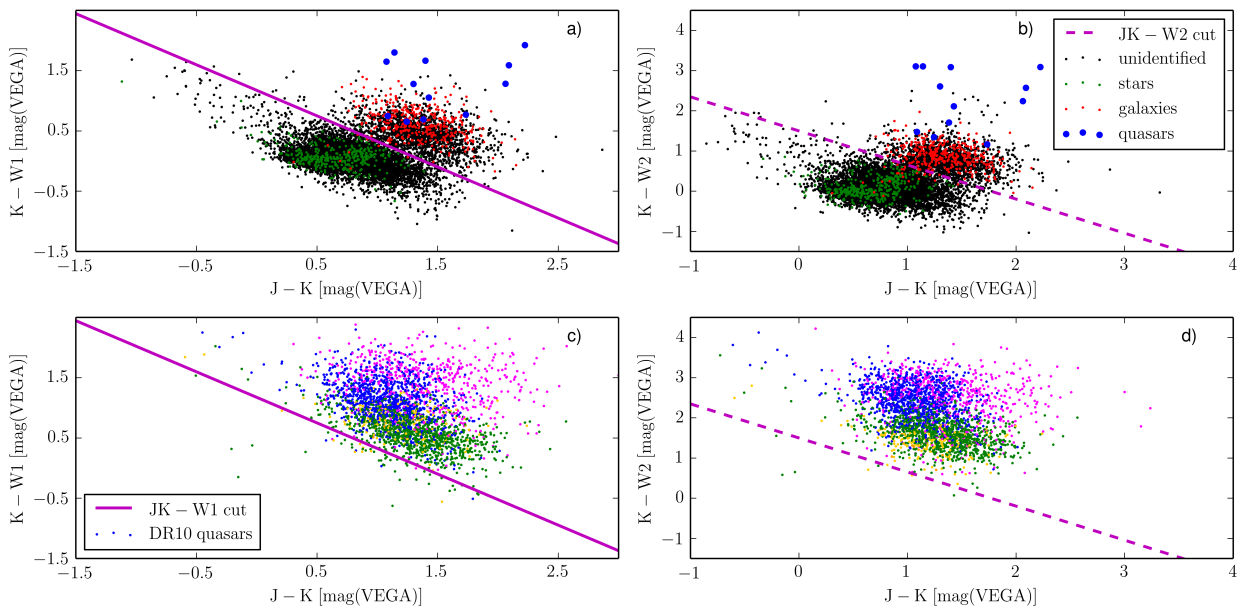

Figure 1: In this figure we show our two WISE-2MASS color criteria to select quasars. Panel a) shows the JK-KW1 color cut (magenta line) of all objects in a field of $\sim 25\,\mathrm{deg}^2$. The black dots are unidentified sources, while for the colored dots spectral classification from SDSS is available. Red dots are galaxies, green dots are stars and big blue dots are quasars. The color cut clearly divides the stars and galaxies/quasars. Panel b) shows the JK-KW2 color cut (dashed magenta line) while all other symbols are the same as in Panel a). The divide between the stars and the galaxies and quasars is even stronger in this color cut. Panel c) and d) show both color cuts with quasars of the SDSS DR10 quasar catalog. The colors correspond to redshifts: magenta($z = 0-1$), blue($z = 1-2$), green($z = 2-3$), yellow($z = 3-4$), orange($z = 4-5$), red($z = 5-6$). Bot panels show clearly that we expect the quasar population above the color cuts. Selecting our quasar candidates using these infrared color cuts allows us to distinguish between stars and galaxies/quasars very clearly.

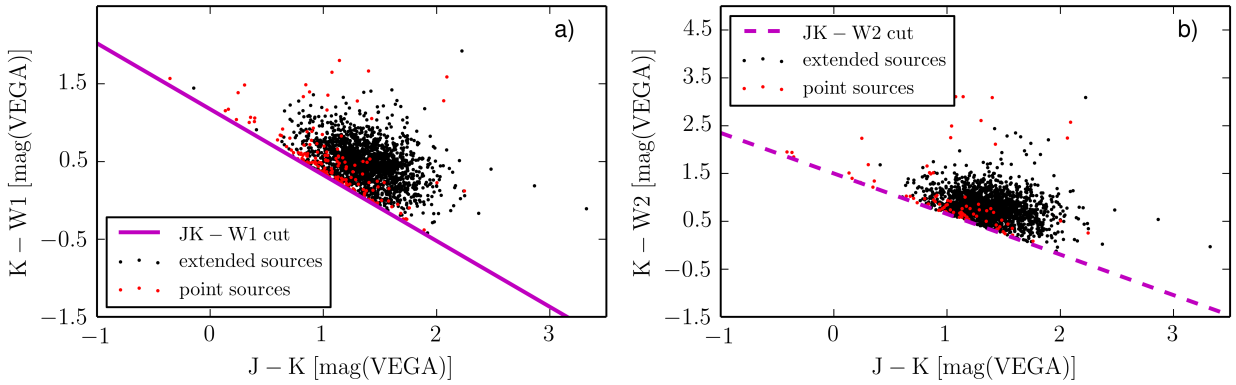

Figure 2: Both panels show our color selected sample of all sources in the $\sim 25\,\mathrm{deg}^2$ field, discerning between extended and point sources using the SDSS photometric identifications. The color cuts are depicted as in Figure 1. The black dots are the extended sources which make up the majority of the sources above the color cuts. The red dots are the point sources, which qualify for being quasar candidates. Distinguishing between point sources and extended ones allows for a very clean selection of sources which are most likely quasars.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Target selection: We select our primary source list on the WISE ALLWISE catalog, using the JK-KW1 color cut ($K - W1 > 1.174 - 0.848 \cdot (J - K)$) to separate stars from quasars/galaxies as shown in Figure 1. The selection criteria further include minimum signal to noise ratios in the W1 and W2 bands ($\mathrm{SNR_{W1}} > 5$, $\mathrm{SNR_{W2}} > 5$). We are selecting all sources with these criteria of a galactic latitude of $l > 30\,\mathrm{deg}$. Our primary source list has about 2.5 million sources.

We match the coordinates of the primary source list with positions of sources from the SDSS DR12 catalog in a $3.96''$ radius, obtaining also spectral classifications if available. The selection criteria for SDSS include the folowing flags for all photometric bands (not SATURATED, not COMSIC RAY, not EDGE) and the following flags in either the i- or z-band (detected in BINNEDx1, not BLENDED, not DEBLEND_NOPEAK or magnitude error < 0.2). We only match to sources that are detected as point sources (type = 6). The matched source list has 26966 objects, from which 4027 are spectroscopically identified (2561 quasars, 1375 stars, 91 galaxies) and 22939 are unidentified.

The JK-KW2 color cut (shown in Figures 1 and 2; $K - W2 > 1.5 - 0.848 \cdot (J - K)$) would reduce the total number of sources to 5503, 2858 of which are unidentified and 2645 of which are identified (2426 quasars, 147 stars and 72 galaxies). We use this JK-KW2 color cut with different intercepts, a brightness criterion in the i-band and a photometric redshift estimate to prioritize our sources.

At last we visually inspect the sources for bad photometry and blended sources in the WISE bands that we have not excluded in our primary target selection.

Configuration and exposure time: We propose to use either the Bok/BCSpec or the VATT/VATTSpec to do spectroscopic identifications of ~ 30 high redshifts quasar candidates ($3 < z < 6$). The Lyman-α line (1215.67Å rest frame) will therefore move from 4862.68Å at $z = 3$ to 8509.69Å at $z = 6$. Using the BCSpec the $400\,\mathrm{g/mm}$ grating in first order blazed at 7506Å and a spectral coverage of 3411Å allows us to identify quasars easily in the redshift range we proposed.

Alternatively we would use the $600\,\mathrm{g/mm}$ grating in first order blazed at 7500Å and with a spectral coverage of 2000Å on the VATTSpec.

In order to address whether these candidates are real quasars, we need the signal-to-noise ~ 5 per resolution element. Our 30 targets have z-band magnitudes of $z_{\mathrm{AB}} < 19$ and we thus require an exposure time of $\sim\ 30 - 60$ minutes for each target at the typical seeing of 1.2". Considering about 10-15 minutes overhead for each target and taking the spectra of flat-fields, lamps and several standard stars each night, we estimate the total exposure time we need is about 37 hours. Therefore, we request 5 dark/grey nights for the observations of 30 high redshift quasar candidates.

We also ask for time on the MMT using the Red Channel spectrograph to follow up targets from the proposed VATT observation run. We expect a success rate of $\sim 50\%$ for our VATT observations. These ~ 15 targets will be relatively bright quasars in the redshift range from $z = 3 - 6$. To evaluate their Black Hole masses and other properties we need higher signal to noise spectra with medium resolution. Depending on the identified redshift we plan to use the two $600\,\mathrm{g/mm}$ gratings blazed at $4800\,$Å and $6310\,$Å and exposure times of ~ 20 minutes per spectrum with ~ 10 minutes of overhead. The total observation time sums up to about 7.5 hours and we therefore ask for one full night on the MMT.

Lunar phases: As possible $z = 3 - 6$ quasars, our targets are faint in the whole optical window and much fainter in the wavelength shorter that 7000Å. The moon light will affect our spectroscopy significantly. We have to carry out our observations in dark and gray nights to ensure the quality of the spectra.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in.* ***(up to one page)***

We request 5 dark/gray nights on either the Bok/BCSpec or the VATT/VATTSpec to observe ~ 30 quasars. We further as for 2 dark/grey nights on the MMT/Red Channel Spectrograph to follow up interesting targets identified the proposed observing run on the VATT. There is no non-UAO telescope associate to this program. This project is part of a pilot survey of bright quasars at redshifts of $3 < z < 6$. If our observations are successful, this project will likely grow into a key component of Jan-Torge Schindler's Ph.D. thesis.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

⋆ We have received 5 nights of grey time (April 21st - April 25th 2015) on the VATT/VATTSpec to carry out our pilot observations.