OBSERVING REQUEST
University of Arizona Observatories

Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term

The Extremely Luminous Quasar Survey (ELQS) and the Bright-End Quasar Luminosity Function at $z{=}3{-}5$

P.I.: Jan-Torge Schindler (SO; *jtschindler@email.arizona.edu*; (520) 621-2494)
CoI(s): Xiaohui Fan (SO), Ian McGreer (SO)

Abstract of Scientific Justification

Studies of the most luminous quasars at high redshift directly probe the evolution of the most supermassive black holes in the early universe and their connection to massive galaxy formation. The Sloan Digital Sky Survey (SDSS) has so far provided the most widely adopted measurements of the quasar luminosity function (QLF) at $z{>}3$.

However, a careful re-examination of the SDSS quasar selection algorithm recently revealed that the SDSS sample is in fact missing a significant fraction of $z{>}3$ quasars at the brightest end. It only recovered $21/36$ (58%) quasars at $z{>}3.0$ with $\mathrm{m_i}{<}17.5$ previously known in the SDSS footprint, and this ratio drops to $7/14$ (50%) for $\mathrm{m_i}{<}17.0$ quasars at this redshift.

We are in the process of finishing our color-selected bright ($\mathrm{m_i}{<}18.0$) quasar survey at $z{>}2.8$ in the SDSS footprint. In 2016 alone we discovered 33 new quasars in this magnitude and redshift range, with 19 being at $z{>}3.0$ with $\mathrm{m_i}{<}17.5$. This success demonstrates the much higher completeness of our survey compared to SDSS and it will allow to place strong constraints on the bright end of the QLF at $z{>}3$ once the survey is completed.

In this program we also plan to extend our survey to $1000\,\mathrm{deg}^2$ of unexplored sky opened up by the recent PanSTARRS data release. Rough estimates show that we will likely triple the number of known luminous quasars in that area. These bright objects are invaluable probes for research on the intergalactic medium, circum-galactic gas, fundamental constants and large-scale structure formation in the Universe through absorption line studies and incited extended Lyα emission.

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			2	'grey'	Oct-Nov	Oct-Dec	no	no
2	VATT		VATTSpec			7	'grey'	Oct-Nov	Oct-Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We ask the MMT follow up run to be scheduled after the time granted for our VATT observations.

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	J233811.51+234650.9	354.547992	23.780593	$m_i = 17.39$, $z_{photo} \approx 3.04$, identification
2	J205426.04+021854.3	313.608474	2.315118	$m_i = 15.72$, $z_{photo} \approx 3.30$, identification
3	J014844.79+250203.0	27.186696	25.034155	$m_i = 17.64$, $z_{photo} \approx 3.02$, identification
4	and ∼97 more targets	270 to 120	-10 to 50	$m_i \leq 17.5$, $z_{photo} > 3.0$, identification
5	J100248.00+663040.2	150.700033	66.511186	$m_i = 17.5$, $z_{spec} \approx 3.92$, spec. followup
6	J034151.17+172049.7	55.463190	17.347153	$m_i = 16.48$, $z_{spec} \approx 3.70$, spec. followup
7	J002448.24+081212.0	6.200994	8.203341	$m_i = 16.97$, $z_{spec} \approx 3.34$, spec. followup
8	and ∼27 more targets	270 to 120	-10 to 50	$m_i \leq 17.5$, $z_{spec} > 3.0$, spec. followup

---

Approval for Instrument Use from PI: ______________________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

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

Scientific Justification

Luminous Quasars are invaluable probes for Extragalactic Astronomy and Cosmology

The wealth of new discovered quasars in the SDSS has transformed our understanding of active super massive black holes (SMBHs). This includes their evolution through cosmic time, their interaction with the galaxy host and their role in re-ionizing the Universe.
However, the formation of SMBHs as well as their rapid growth in the early Universe are still poorly understood. As one of the most important statistics to study the evolution of SMBH, the quasar luminosity function (QLF) at the very bright end at high redshifts allows to tackle those problems.
Furthermore luminous quasars are invaluable probes for the intergalactic medium and Cosmology. Quasars as bright background sources allow to constrain the metallicity of the IGM (Simcoe et al. 2004), the nature of H- and He-reionization (e.g. Worseck et al. 2011), and the statistics of Lyman limit system and damped Lyman-α absorbers (e.g. Prochaska et al. 2005). Luminous quasars offer insight into the morphology and kinematics of their circum-galactic gas through absorption line studies (Prochaska et al. 2014) or the mapping of extended Lyα emission illuminated by active SMBH (e.g. Cantalupo et al. 2014). Unfortunately very luminous quasars, as tracers of the most massive SMBHs, are extremely rare.
On top of that, we discovered that the SDSS has missed many bright quasars at $z = 3 - 4$, rendering the bright end of the QLF at those redshifts highly unconstrained. In past years we have started a survey of bright (m_i<18.0) high redshift quasars (z>2.8), circumventing the limitations of purely optical surveys with our near-infrared based candidate selection.
We propose to i) complete our survey of bright $z = 3-5$ quasars in the SDSS fall footprint and ii) extend it to a mostly unexplored region of $\approx 1000\,\deg^2$ opened up by the recent PanSTARRS data release.
The first part of this program will result in a new estimation of the bright high redshift QLF by summer 2018. The second part will discover many new luminous quasars that will serve as invaluable targets for studies of the IGM and Cosmology. This work, complemented by a southern component we proposed for using the SOAR telescope, will be part of a uniform all-sky survey of bright high redshift quasars.
For this program we request 7 grey nights on the VATT using the VATTSpec spectrograph to carry out identifications of our $\sim$100 candidates. We further ask for 2 grey nights on the MMT to take $\sim$ 50 high signal-to-noise (S/N$\approx$50) spectra to allow for precise redshift and emission line measurements as well as identification of strong broad absorption line (BAL) features and damped Lyman-α (DLA) systems for future studies.

The SDSS quasar selection rejected bright $\mathrm{z} > 3.0$ quasars

Bright high redshift quasars are highly incomplete in the SDSS DR7 and DR12 quasar catalogs compared to estimates from the QLF of Richards et al. (2006, hereafter Ri06). Previous surveys found 36(14) quasars with $\mathrm{m_i}$<17.5 ($\mathrm{m_i}$<17.0) at z>3.0 of which only 21(7) were re-identified with the SDSS quasar selection. Therefore roughly 40% of previously known quasars were missed by the SDSS selection.
We illustrate this in Figure 1, where we compare quasar counts from the DR7 and DR12 quasar catalogs with the prediction of the QLF (Ri06) and all known quasars in the SDSS footprint from the Million Quasar catalog (Flesch et al. 2015).
The four panels show the cumulative quasar counts as a function of apparent i-band magnitude for four different redshift bins. The blue region corresponds to quasars in the SDSS DR7/DR12 quasar catalogs, whereas the red regions show the counts of quasars not targeted/identified by SDSS but found in the Million Quasar catalog (MQC). The discrepancy between those regions is evident in the top right and bottom left two panels, which implies that especially bright quasars at redshifts between 3.0<z<4.0 were missed by SDSS. The predictions from the QLF of Ri06 and Ross et al. (2013) are shown as solid black and grey lines. For quasars at redshifts z>3.0 and brighter than m_i<17.5, we would expect 166 objects, whereas only 77 are observed (58 in SDSS). Using a more complete target selection, we expect to find $\sim$90 new bright $z = 3-5$ quasars. In fall 2016 we were already able to discover 19 of those objects. Given the incompleteness of bright z>3 quasars in SDSS a thorough re-evaluation of the QLF at z>3 is necessary.

A candidate selection based on near-infrared photometry complemented by SDSS

Our group has developed a new selection technique based on infrared photometry of the WISE ALLWISE catalog in conjunction with the 2MASS point source catalog. Using a JKW2 color cut allows for a clean rejection of the majority of stars, whose spectral energy distributions fall steeply towards the mid-infrared.

Of all SDSS DR7/DR12 quasars with ALLWISE and 2MASS photometry more than 94% are in our JKW2 inclusion region. On the other hand 99.6% of spectroscopically identified stars in a test region of $900\,\mathrm{deg}^2$ are excluded. Therefore this color cut has high completeness while guaranteeing low contamination.
Our further photometric redshift estimation and candidate selection is based on Random Forest regression and classification. Using the full color space (SDSS+2MASS+WISE), we are able to accurately determine redshifts and candidate classes (STAR/QSO) using the SDSS DR7+DR12 quasars and SDSS DR13 spectroscopically identified stars as training samples. We combine this information with the traditional SDSS quasar inclusion regions for $z > 3.0$ quasars (Ri06), without the restraining magnitude cuts that bias against bright quasars.
Our candidate selection techniques recover all but one quasar missed by the SDSS selection.

The success of our extremely luminous quasars survey (ELQS)

Over the past two years we have discovered 38 new, bright (m_i<18.0) high redshift quasars (z>2.8). In total we have surveyed 238 candidates out of which 89 were confirmed as quasars.
Figure 1 shows the progress of our survey (green regions) compared to the SDSS DR7/DR12 quasar catalogs and Million Quasar catalog in cumulative number counts as a function of apparent i-band magnitude. The SDSS quasars are a subset of the Million Quasar catalog (MQC), while our work adds to both of them. Compared to the SDSS quasar catalogs we could double the number of discovered quasars with $m_i < 17.5$ at $3.5 < z < 4.0$ (an increase of 50% compared to the MQC).
We show the redshift magnitude distribution of our objects (red filled circles) compared to the MQC (blue histogram) in Figure **??**. We clearly reach the goal of our selection to survey the brightest quasars at $2.5 < z < 5.0$ as evident from the distribution of the red dots. One object at $z = 3.7$ clearly stands out with an absolute magnitude of $M_i = -30.8$. It is the brightest object in our survey. There are two other known objects at this redshift range with brighter absolute i-band magnitudes. However, both are well known quasar lenses from the literature. Based on more recent PanSTARRS and UHS photometry our object shows no indication of being lensed, which makes it the intrinsically most luminous quasars at $z > 3.2$. We show the discovery spectrum of this quasars in Figure 3.
That we were able to discover so many new bright quasars in a well surveyed area demonstrates the high completeness of our selection technique. Independent of more discoveries, our survey's completeness will allow to place strong constraints on the quasar number counts per unit area. Thus we will be able to robustly measure the bright-end QLF at z=3−5 *for the very first time.*

Extending the ELQS to unexplored areas using PanSTARRS

The recent publication of the first PanSTARRS data release has opened up another $\approx 10000\,\mathrm{deg}^2$ in addition to the full SDSS footprint, providing deep optical photometry. In our pursuit to build an all-sky spectroscopic catalog of extremely luminous quasars using our near-infrared based candidate selection, we plan to extend our survey to these large areas, that have not yet been mapped with quasar surveys. Therefore we plan to expand our survey to an unexplored region $\approx 1000\,\mathrm{deg}^2$ in the northern fall sky as part of this proposal. This extension will be complemented by a campaign in the southern hemisphere using the SOAR telescope targeting an area of $5400\,\mathrm{deg}^2$ in the PanSTARRS footprint.
Any new extremely luminous quasars are invaluable probes that will stimulate extragalactic science and cosmology and benefit the whole science community.

References

Cantalupo, S. et al. 2014, Nature 506, 63C
Flesch, E. 2015, PASA 32, 10F
McGreer, I. et al. 2013, ApJ, 768, 105
Prochaska, J.X. et al. 2005, ApJ 635,123
Prochaska, J.X. et al. 2014, ApJ 796, 140P
Richards, G. T. et al. 2002, ApJ, 123, 2945
Richards, G. T. et al. 2006, AJ, 131, 2766
Ross, N.P. et al. 2013, ApJ 773, 14R
Schneider, D.P. et al. 2010, AJ 139, 2360S Simcoe, R.A. 2004, ApJ, 6060, 92
Worseck et al. 2011, ApJ 733L, 24W

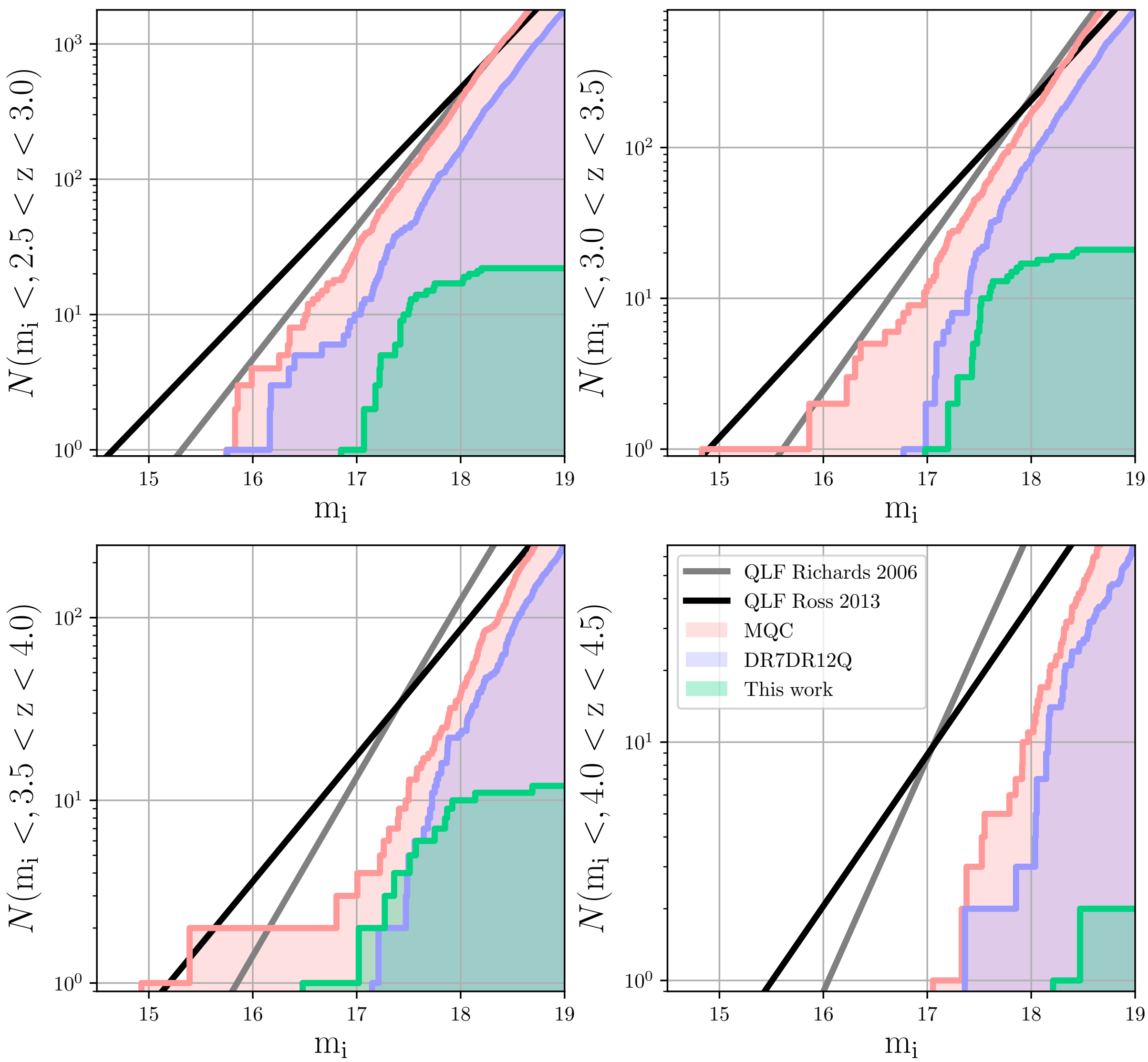

Figure 1: The figure compares the previously known cumulative quasar counts in the SDSS footprint (red/blue) in four different redshift bins to our newly discovered objects ("This Work", in green) as a function of i-band magnitude. The two catalogs of previously known quasars are the Million Quasar Catalog (Flesch et al. 2015) and the combined SDSS DR7 and DR12 quasar catalogs (Schneider et al. 2010, Paris et al. 2015). The Million quasar catalog includes the SDSS sources. The differences to the combined SDSS DR7 and DR12 quasar catalogs displays multiple limitations of the SDSS survey to find bright high redshift quasars (e.g. fiber collision, selection bias against bright sources etc).

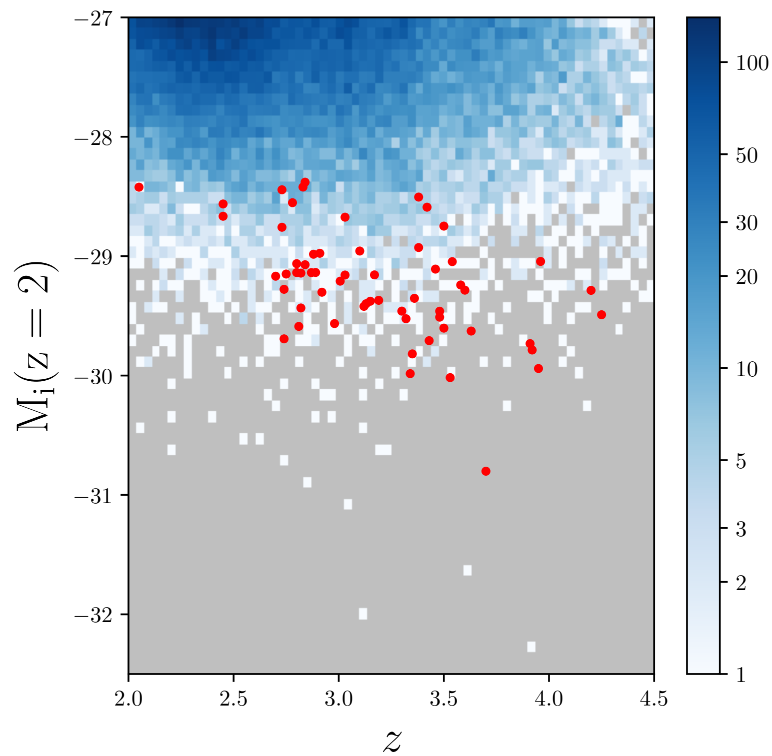

Figure 2: The distribution of our newly discovered quasars (red dots) against the known quasars in the SDSS footprint (blue histogram, Million Quasar Catalog) as a function of redshift and absolute i-band magnitude k-corrected to $z = 2$ (see Ross et al. 2013). These are the results from our previous survey targeted at $z \approx 2.5 - 4.0$. The extremely luminous quasar J0341+1720 is clearly visible at $z \approx 3.7$ and is the intrinsically brightest source at $z > 3.2$. The two other data points much brighter at similar redshifts are confirmed quasar lenses from the literature.

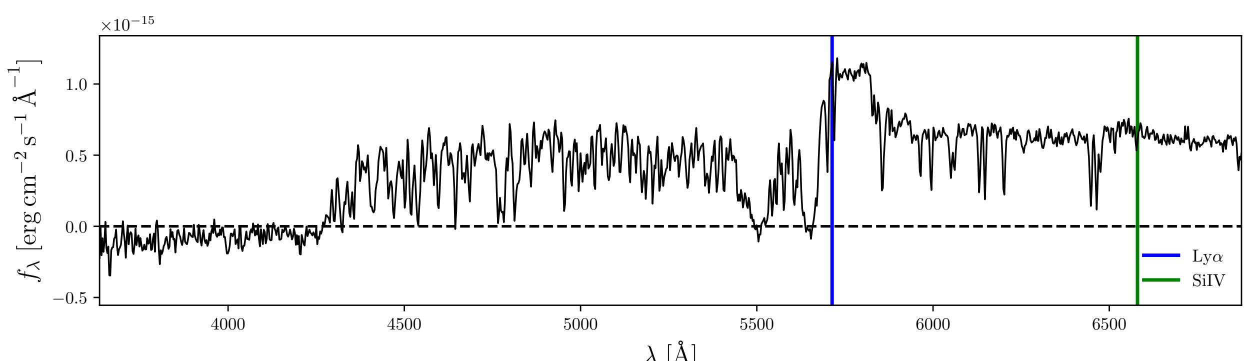

Figure 3: This is the discovery spectrum of J0341+1720, the most luminous QSO at $z > 3.2$ with $M_i(z = 2) \approx -30.8$ at $z = 3.7$. The Lyman-α forest below $7515\mathring{A}$ is clearly visible up to the Lyman limit of $\approx 4300\mathring{A}$, where all flux is absorbed.

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)***

An infrared based parent catalog

In the past two years we have developed an infrared target selection technique, using the WISE ALLWISE catalog in combination with 2MASS photometry to select relatively bright quasars. The infrared photometry allows to clearly distinguish between stars of any spectral type and quasars/galaxies. We determined a JKW2 color cut ($K - W2 > 1.5 - 0.848 \cdot (J - K)$), which has an estimated completeness of $\sim 95\%$ based on the SDSS DR7/DR12 quasar catalogs and rejects 99.6% of the stars in a $900\,\mathrm{deg}^2$ test field.
We use this color-cut to establish an infrared based catalog, which is then matched to SDSS DR13 optical photometry within a $4''$ aperture.

State-of-the-art quasar candidate selection

We have thoroughly investigated how to use machine learning, SED fitting or color-color regions to classify quasars and estimate their photometric redshifts. In conclusion we decided to use Random Forest classification on a training set of empirical DR7 and DR12 quasars versus DR13 spectroscopically identified stars to estimate the quasar probability of the object. Validations on test samples drawn from the same empirical quasar set have shown a completeness of over 90% for $z > 2.5$ quasars, with a slightly lower efficiency. We employ the same machine learning technique for regression to estimate the photometric redshift of our quasar candidates based on the same empirical quasar training sample. It compares favorably with other photometric redshift estimators. Photometric redshift as well as the classification probability are both used to select the candidate sample for our observations. In addition we have used slightly modified color inclusion regions of Richards et al. (2002) for $z > 3.5$ quasars. The regions are 1) GRI (σ_i<0.2, $u-g$>1.5, $g-r$>0.0, $g-r$>1.7 or $r-i$<$0.54\cdot(g-r)-0.358$, $i-z$<-1.0), 2) GRIZ ($u-g$>1.4, $g-r$<1.3, $i-z$>-1.0, $g-r$<$0.44\cdot(u-g)-0.46$) and 3) RIZ (σ_i<0.2, $r-i$>0.6, $i-z$>-1.0, $i-z$<$0.52\cdot(r-i)-0.212$). These regions are designed to yield a high efficiency in finding quasars and form our high priority sample. The combination of the inclusion regions and the Random Forest selection achieved an efficiency of around 40% in our previous observations, while focusing on high completeness.

Configuration and exposure time estimates

We propose to use the VATT/VATTSpec to carry out spectroscopic identifications of $\sim$100 z=3$-$5 quasar candidates. The Lyman-α line (1215.67Å rest frame) will therefore move from 4863Å at z=3 to 7296Å at $z = 5$. We plan to use the $300\,\mathrm{g/mm}$ grating in first order blazed at 5000Å and with a spectral coverage of 4000Å on the VATTSpec. We show an example spectrum in Figure 3.
In order to address whether these candidates are real quasars, we need a signal-to-noise of ~ 5 per resolution element. Our ~ 100 targets have i-band magnitudes of $m_i \lesssim 18.0$ and we thus require an exposure time of $\sim$20 minutes for each target at the typical seeing of 1.2". Considering about 10 minutes overhead for each target, we estimate the total observation time to be about 50 hours. *Therefore, we request 7 grey nights for the identification of* ~ 100 *high redshift quasar candidates.*
In order to precisely measure redshifts and emission line widths, we need high signal-to-noise spectra (S/N$\approx$50). These spectra are further necessary for the identification of strong BAL features and DLA systems. We have 19 bright high redshift quasars from our fall 2016 campaign and estimate to find another ~ 30 with the new observing run on the VATT, summing up to a total of ~ 50 targets to follow up. Dependent on the redshift of the target, different configurations might be needed. We plan to use the two $600\,\mathrm{g/mm}$ gratings blazed at 4800 Å and 6310 Å and exposure times of $\sim$15 minutes per spectrum with $\sim$5 minutes of overhead. We estimate the total observation time to be about 17 hours and *we therefore ask for two grey nights on the MMT to fully characterize our discovered quasars. If we were granted less time on the VATT or would loose time to weather, we can finish our candidate identifications using the MMT to ensure the success of the project.*

Lunar phases: As possible z=3$-$5 quasars, our targets, although "bright" for quasars are moderately faint at wavelength shorter than 5000Å. The moon light will affect our spectroscopy and therefore we have to carry out our observations in grey 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**)*

Scope:
i)The goal of the PI's thesis is to measure the luminosity function of high-redshift quasars at the brightest end, and to characterize the evolution of the most massive black holes in the early universe. The observations proposed here will form the PI's thesis sample. We expect the proposed observations to be sufficient to calculate a new estimate of the bright end QLF at at $z = 3{-}5$ by summer 2018.

ii) We are building on our expertise for the proposed expansion of our extremely luminous quasar survey to the PanSTARRS footprint. The PanSTARRS survey covers all sky at $\delta > -30$ and together with ALLWISE and 2MASS allows us to construct a uniform all-sky survey of bright quasars. It opens up a region of $\sim 10000\,\mathrm{deg}^2$ unmapped by any optical quasar surveys. This proposal aims to pilot this project with a new area of $\sim 1000\,\mathrm{deg}^2$ in the fall northern sky and is complemented by another proposal to NOAO to map $5400\,\mathrm{deg}^2$ at the southern galactic cap. It will provide the community with invaluable targets to study the IGM and constrain cosmological parameters.

Request:
We request 7 grey nights on the VATT using VATTSpec to observe $\sim$100 bright quasar candidates at $z = 3{-}5$. For further characterization of the newly found quasars and our previously discovered ones, we need high signal-to-noise spectra. To obtain them with the VATT spectrograph is too time consuming and therefore we ask for 2 grey nights on the MMT using the RedChannel spectrograph to carry out these observations. However if we get granted less time on the VATT or we loose observation time due to weather, we can finish our candidate identification using the MMT to ensure the success of this project.

Summary of success and awarded time:
Up to now we have discovered a total of 89 quasars out of 238 observed candidates since we started our survey. Out of these 89 quasars 38 have dereddened i-band magnitudes of $m_i < 18.0$ at a redshift $z \geq 2.8$. As shown in Figure 3 above, these objects are very bright compared to the overall quasar magnitude-redshift distribution. Our efficiency in finding quasars in general is around 40% on average, whereas very bright ($m_i < 17.5$) quasars at $z > 3.0$ are much more rare and their efficiency drops to 15%.

Out of the 27 awarded nights on the VATT telescope we lost 46% of the time ($\sim$ 12 nights), mainly due to bad weather. We further received 1 night at the MMT in November 2015 and 2 TBS nights on the BOK telescope in fall 2016.

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**)*

A survey of $\mathbf{m_i}$<18.5 quasars at $\mathbf{z}\geq$3.0

- ⋆ We have received 5 nights of grey time (April 21st - April 25th 2015) on the VATT/VATTSpec to carry out pilot observations for the survey.
- ⋆ We continued this survey with 5 nights of grey time (October 8th - October 12th 2015) on the VATT/VATTSpec and 1 night of grey time (November 3rd 2015) on the MMT/Red Channel Sp. for follow up observations of the successfully identified quasars.
- ⋆ During the spring semester of 2016 we received 10 nights of grey time (March 10th-15th, April 10th-13th) on the VATT with VATTSpec to continue our m_i<18.0 $z\geq$2.8 survey. We confirmed 9 new quasars at $z > 2.8$ and found 18 quasars in total.
- ⋆ In the 2016 fall semester we received 7 nights of VATT time for spectroscopic identification and were able to confirm 24 new m_i<18.0 quasars a $z > 2.8$, 32 in total.
- ⋆ In the 2017 spring semester we were awarded 10 nights of VATT time for spectroscopic identification and 2 nights of MMT time for follow-up. The observations have not been carried out yet.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*