OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **Proposal type:** short-term

Identifying $z \sim 6$ Quasars in SDSS Overlap Regions

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Abstract of Scientific Justification

We propose to use Bok/90Prime to improve the i and z-band photometry for a large sample of i-dropout objects ($z \sim 6$ quasar candidates) selected in the SDSS overlap regions. Many SDSS observing runs overlap, leading to duplicate observations over nearly 4000 square degrees. These overlap regions provide a unique dataset for us to search for $z \sim 6$ quasars. The Bok photometry will significantly reduce the number of contaminants, and thus increase our quasar selection efficiency. Recently we have discovered seven new quasars in the SDSS overlap regions using our previous Bok/90Prime and the MMT/Red channel observations. These quasars are about 0.5 mag fainter than those found in SDSS single-epoch images. With the new Bok observations, we will complete our photometry for all our i-dropouts. We also propose to use the MMT/Red channel to observe a list of promising quasar candidates that we previously identified in the same regions. With the proposed and follow-up observations, we expect to find 5–10 new quasars. This sample, combined with previous $z \sim 6$ quasar samples, will be used to determine the quasar luminosity function at $z \sim 6$, to improve the current constraints on the reionization history, to measure the metallicity in high-redshift quasar environments, and to study the accretion history of massive black holes at early epochs.

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	90	PF	90Prime			3	grey	Mar–May	Feb–Jun	no	no
2	MMT	f/9	Red			1	grey	Mar–May	Feb–Jun	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None.

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	SDSS i–dropout objects	8∼17 h	0∼70 deg	$z_{AB} < 20.5$

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 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

Scientific Justification

(I) High-redshift quasars at the end of cosmic reionization

High-redshift quasars provide a powerful tool to study the early universe. The first $z \sim 6$ quasars (e.g. Fan et al. 2001, 2003) were found by the SDSS. Most of these quasars are very luminous ($M_{1450} < -26.5$ mag). Deep near-IR spectroscopy has shown that these quasars harbor billion-solar-mass black holes and emit near the Eddington limit, suggesting the rapid growth of central black holes in the early epoch (e.g. Jiang et al. 2007). Their broad emission lines exhibit solar or supersolar metallicity, indicating that vigorous star formation and element enrichment have occurred in the host galaxies (e.g. Kurk et al. 2007). Their optical absorption spectra show that the state of the IGM at $z \sim 6$ is close to the reionization epoch (e.g. Fan et al. 2006). Furthermore, the mid/far-IR, mm/sub-mm, and radio observations of these quasars have provided rich information about dust emission and star formation in their host galaxies (e.g. Wang et al. 2011). Therefore, $z \geq 6$ quasars are essential in understanding black hole accretion, galaxy evolution, and the IGM state in the first billion years of cosmic time.

In recent years, more than 60 quasars at $z \sim 6$ have been discovered. The SDSS has pioneered the discovery, followed by the CFHQS survey (e.g. Willott et al. 2010) and the UKIDSS survey (e.g. Mortlock et al. 2011). So far the SDSS has discovered ∼30 quasars from its main imaging survey (e.g. Fan et al. 2001, 2003) and its deep Stripe 82 survey (e.g. Jiang et al. 2008, 2009). The UKIDSS has found several quasars, including the most distant quasar known at $z = 7.08$ (Mortlock et al. 2011). The CFHQS produced 19 quasars down to a fainter luminosity limit. Most recently, the Pan-STARRS1 survey and the VISTA survey started to produce $z \geq 6$ quasars (e.g. Morganson et al. 2012; Venemans et al. 2013). The number of $z \geq 6$ quasars known is increasing steadily. However, the number of luminous quasars ($M_{1450} < -26$ mag) did not change much since the completion of the SDSS main survey, because the discovery of such objects requires surveys of a few thousand square degrees of the sky. On the other hand, luminous quasars are more useful than faint quasars in studies such as the reionization history and quasar chemical enrichment, because it is very time-consuming to obtain high-quality optical and near-IR spectra for faint quasars.

The SDSS overlap regions provide a unique opportunity to search for luminous quasars in a very wide area. The SDSS imaging survey was conducted in drift scan mode along great circles. Many SDSS observing runs overlap, leading to duplicate observations over a very large area. The duplicate observations allow us to select quasar candidates that are slightly fainter (∼0.5 mag) than quasars selected from SDSS single-epoch data. They ensure that the candidates are free of spurious detections (such as cosmic rays), which is particularly useful for objects with single-band (z) detections. The total area of the overlap regions reaches nearly 4000 square degrees. We have conducted a large survey with Bok and the MMT in the past two years, and found seven new $z \sim 6$ quasars in the SDSS overlap regions (Figures 1 and 2). We also recovered all previously discovered quasars that are in the overlap regions. We plan to complete the survey over all SDSS overlap regions with the proposed observations.

(II) Proposed observations and sciences

We are carrying out a complete survey of $z \sim 6$ quasars in the SDSS overlap regions. The quasar candidate selection procedure and follow-up observations are described in the next section. We have selected a total of ∼300 i-dropout objects ($i_{\rm AB} - z_{\rm AB} > 2.2$) down to 7σ detection in the z band. A significant fraction of contaminants were caused by large photometric uncertainties in the i and z bands (via the color cut of $i_{\rm AB} - z_{\rm AB} > 2.2$). We are using Bok/90Prime to improve the i and z-band photometry of i-dropout objects. Our goal is to achieve $i_{\rm err} < 0.15$ and $z_{\rm err} < 0.08$ for a typical $z_{\rm AB} = 20.5$ mag i-dropout object. The current photometric uncertainties are about $i_{\rm err} = 0.35$ and $z_{\rm err} = 0.15$. The improved photometry will largely reduce the number of contaminants, and allow us to efficiently select quasar candidates. Follow-up observations will be carried out in the future to identify quasars.

We have already observed about 200 i-dropouts in the past two years. Here we request 3 Bok nights to finish the rest 100 objects. We have found seven quasars from the list of quasar candidates with improved photometry, and we request 1 MMT night to identify the remaining promising candidates obtained from previous observations. With the proposed and follow-up observations, we expect to find 5–10 new quasars down to $z_{\rm AB} = 20.5$ mag in the SDSS overlap regions. This is based on the quasar luminosity functions by

Jiang et al. (2009) and Willott et al. (2010). The new quasars together with currently known quasars will be used to study:

($\star$) Quasar luminosity function (QLF) at $z \sim 6$.
The bright-end slope of the quasar luminosity function (described by a power-law) is very steep (about –3; Fan et al. 2006; Jiang et al. 2009), so a greater depth results in a much higher spatial density. We expect to discover 20–25 quasars over the whole SDSS overlap regions. This will significantly improve the measurement of the QLF at this redshift.

($\star$) History of reionization.
Detection of complete Gunn-Peterson troughs among the highest-redshift quasars indicates a rapid increase of the IGM neutral fraction, suggesting that we have reached the end of reionization epoch (Becker et al. 2001). Meanwhile, reionization is not a uniform process, rather, there is large line-of-sight variation in the IGM properties at the end of reionization (Fan et al. 2006); detailed mapping of reionization history is still severely limited by a small number of bright sources available. Our new sample will improve measurements of the inhomogeneity of reionization process and constraints models of reionization and nature of ionizing sources at high redshift. This can only be done by bright quasars, since deep spectroscopy of faint $z \sim 6$ quasars is very time-consuming.

($\star$) Quasar contribution to the UV background.
The reionization of the universe ends at $z \sim 6$, but the individual contributions of galaxies and quasars to reionization are still unclear. Current estimate on the quasar contribution to the UV background at $z \sim 6$ is quite uncertain, partially due to the small sample of known quasars. The new observations will increase the number of quasars, and put a better constraint on the total quasar contribution to reionization.

($\star$) History of black hole accretion.
At $z > 6$, quasar evolution is limited by the number of e-folding times available for black hole growth, thus the QLF at $z \sim 6$ puts strong constraints on models of the earliest black hole evolution, especially whether standard radiatively efficient Eddington accretion from stellar seeds is still allowed, or, alternative models of black hole birth (e.g. from intermediate-mass black holes) and accretion (e.g. super-Eddington) are required.

($\star$) Emission lines and chemical abundances.
We will measure emission line properties of the new quasars. These measurements trace the chemical enrichment process in quasar environments and constrain models of star formation in early epoch.

These quasars also provide targets for further observations, such as X-ray, IR, mm/sub-mm and radio observations, to understand the SEDs of high-redshift quasars, metallicity of the quasar environment, the evolution of metals in the IGM at high redshift, and the relation between quasar activity and the presence of dust and starburst. In addition, we will discover a sample of L and T dwarfs in the same survey area, and study the luminosity and mass functions of brown dwarfs.

References

Becker, et al. 2001, AJ, 122, 2850
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Jiang, et al. 2008, AJ, 135, 1057
Jiang, et al. 2009, AJ, 138, 305
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Kurk, et al. 2007, ApJ, 669, 32
Morganson, et al. 2012, AJ, 143, 142
Mortlock, et al. 2011, Nature, 474, 616
Venemans, et al. 2013, AJ, 779, 24
Wang, et al. 2011, AJ, 142, 101
Willott, et al. 2010, AJ, 139, 906

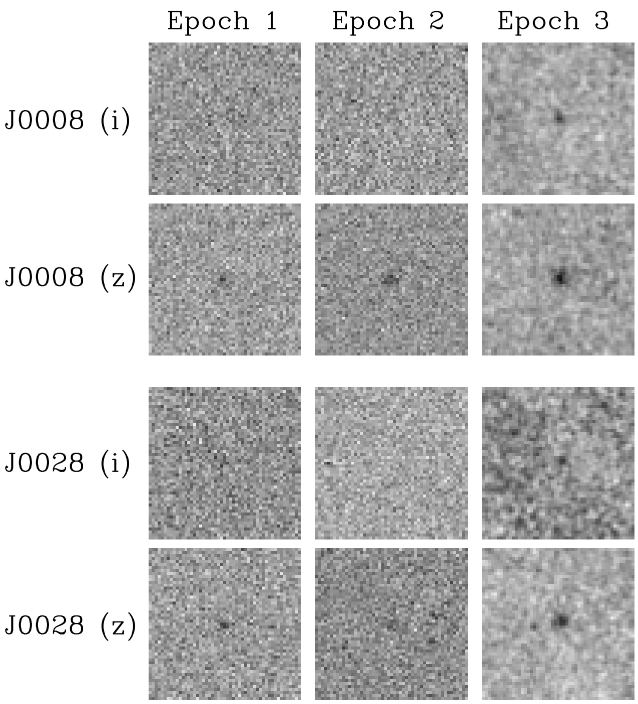

Figure 1: Multi-epoch observations of two newly discovered $z \sim 6$ quasars J0008 and J0028 in the i and z bands. In the SDSS observations (Epoch 1 and 2), the two quasars were not (or barely) detected in the i band, and were very weak ($5\sigma - 7\sigma$) in the z band. The new Bok 90Prime observations (Epoch 3) clearly detected them in the i band, and have strong detections ($\geq 10\sigma$) in the z band. The proposed observations will improve i and z-band photometry for a large, statistically complete sample of i-dropout objects.

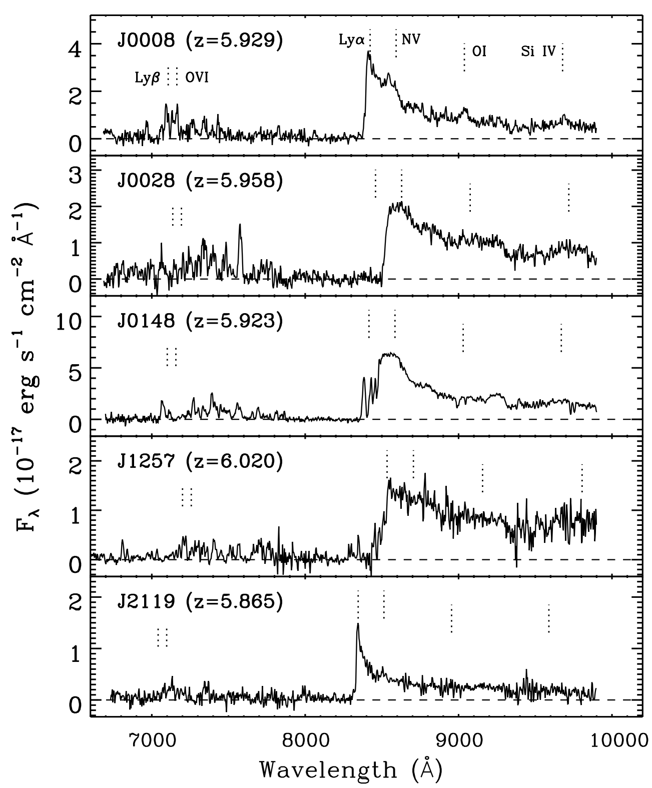

Figure 2: A sample of newly discovered quasars in SDSS overlap regions. The spectra were taken from the MMT Red Channel Spectrograph. Each spectrum has been scaled to match the corresponding z-band magnitude, thereby placed on an absolute flux scale.

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)***

(I) Quasar candidate selection procedure

Because of the rarity of high-redshift quasars and overwhelming number of contaminants, our selection procedure of $z > 5.7$ quasar candidates includes the following separate steps:

1. Select i-dropout sources from the SDSS overlap regions.
Objects with $i_{\rm AB} - z_{\rm AB} > 2.2$ and $z_{\rm AB} < 20.5$ are selected as i-dropout objects. These objects are not detected in any of the ugr bands. The majority of them are late M and L/T dwarfs.

2. Improve the i and z-band photometry of i-dropouts.
Although these i-dropouts are free of cosmic rays due to duplicate observations, their photometric uncertainties are large. To efficiently select quasar candidates, better i and z-band photometry is needed. We propose to use Bok/90Prime to improve the i and z-band photometry. Based on our pilot study, improved photometry can remove 70-80% of contaminants.

3. J-band photometry of i-dropout objects.
We then carry out J-band photometry of i-dropout objects to separate quasar candidates and brown dwarfs in the $i_{AB} - z_{AB}$ vs. $z_{AB} - J$ color-color diagram.

4. Follow-up spectroscopy of quasar candidates.
The final step is to carry out optical spectroscopic observations to identify quasar candidates.

(II) Proposed observations and follow-up spectroscopy

We will observe about 100 i-dropouts with Bok. The goal is to achieve $i_{\rm err} < 0.15$ and $z_{\rm err} < 0.08$ for a typical $z = 20.5$ mag i-dropout. The current photometric uncertainties are about $i_{\rm err} = 0.35$ and $z_{\rm err} = 0.15$. The on-source integration time, estimated based on our previous observations, is 5 min in i and 3 min in z for a $z = 20.5$ mag i-dropout. The observations will be done semi-automatically with a series of observing scripts. The overhead time is significant, including setup time, readout time, telescope slewing, filter change, etc. These objects are faint in the i band, so we request grey time. In summary, we request a total of 3 grey nights.

We also request one MMT night to identify a list of $\sim$20 quasar candidates obtained from our previous observations. The Red Channel has a red-sensitive CCD with excellent QE up to 1μm, so it is efficient to identify objects at $z > 6$. The spectroscopic observations consist of two parts: (1) For each candidate, we will take a short exposure ($\sim$ 10 min), which is usually sufficient to identify a quasar under normal weather conditions. (2) For each new quasar, we will take a long exposure (1–2 hr) to achieve a high S/N spectrum for publication. The high S/N spectra will also be used to measure the emission line properties of the new quasars. Our targets are faint, so we request grey time.

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 have been awarded about 10 Bok nights and 2 MMT nights for this program. We found seven new quasars at $z \sim 6$. A paper based on these quasars is ready to submit. Here we request 3 Bok nights to complete the i and z-band photometry of i dropouts, and 1 MMT night to identify a list of candidates obtained from previous observations. We will request 1 MMT night to finish the program in the future.

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)***

Sep 2012: three nights with the MMT/Red channel. *We lost all the time due to a storm in the end of the monsoon season.*

⋆ Sep–Oct 2012: four nights with Bok/90Prime. We lost one night due to bad weather. The rest three nights were used to improve the i and z-band imaging of $z \sim 6$ quasar candidates in the SDSS overlap regions.

⋆ Mar–Apr 2013: four nights with Bok/90Prime. We lost one night due to bad weather. Another night was cloudy and was used to improve the i and z band photometry of $z \sim 6$ quasar candidates in the SDSS overlap regions. The rest two nights were used for deep i-band imaging of the UKIDSS DXS fields.

Mar 2013: half night with LBT/LUCI (queue mode). We got 3.5 hour on-source integration for a $z \simeq 7.7$ LAE candidate. A paper based on these data together with the LUCI data taken in 2012 has been published (Jiang, et al. 2013, ApJL, 771, 6).

Apr 2013: half night with LBT/MODS. *AZ lost the whole AZ block due to bad weather.*

⋆ Apr 2013: two nights with MMT/Red channel. The program was used to identify $z \geq 6$ quasar candidates in the UKIDSS DXS fields selected from our Bok data. We met very bad seeing of $2'' \sim 4''$ throughout the run, so we had to observe much brighter backup targets. We confirmed several bright quasars at $z \sim 5$, and two bright quasars at $z \sim 6$ in the SDSS overlap regions.

Jul 2013: two nights with the MMT/SWIRC. *The monsoon season had started, and we did not open the dome.*

Sep 2013: two nights with MAG1/IMACS. *We lost almost the whole run due to bad weather. We only got 2 hour good data.*

⋆ Oct 2013: two nights with the MMT/Red channel. The time was used to identify $z \sim 6$ quasars in the SDSS overlap regions. We found three new quasars.

Jan 2014: three nights with Bok/90Prime. The time was used to image the UKIDSS DXS fields.

Feb 2014: three nights with the MMT/Red channel. *We lost all the time due to bad weather.*

⋆ Mar–Apr 2014: seven nights with Bok/90Prime. The time was used to image the UKIDSS DXS fields, and to improve the i and z band photometry of $z \sim 6$ quasar candidates in the SDSS overlap regions. *A paper based on a total of 7 $z \sim 6$ quasars in the SDSS overlap regions is ready to submit. This paper uses the data taken with Bok and the MMT in the runs mentioned above.*