OBSERVING REQUEST
Telescope Access Program, China

Year: 2015 **Term:** Feb–Jul **Proposal type:** short-term

Finding quasars in the post-reionization epoch

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CoI(s): Xue-Bing Wu (KIAA), Xiaohui Fan (U.Arizona/KIAA), Feige Wang⋆ (PKU), Qian Yang⋆ (PKU), Xiaoyi Dong (PKU)

Abstract of Scientific Justification

Previous studies of quasars at $z > 6$ show that the end of the reionization epoch is around redshift $z \sim 6$. Recent work indicates that the tail of reionization extends to significantly lower redshift, and might have only fully completed by $z \sim 5$. Therefore, quasars at $5 < z < 6$ provide crucial probes to the IGM during the post-reionization epoch. However quasars with redshifts $5.1 < z < 5.7$ are difficult to be found because their optical colors are similar to those of late-type stars, resulting in a glaring gap in the redshift distribution for known quasars at $5.1 < z < 5.7$. The lack of quasars at this redshift range also lead to large uncertainties in black hole mass function and quasar luminosity function at early epoch. We have developed a method to find $z > 5$ quasars based on the combination of optical and near-IR colors, and have successfully identified 19 quasars with $z > 5$. We have been allocated 1.5 nights with MMT/Red Channel for spectroscopic confirmation of our quasar candidate in Dec 2014. For 2015A, we propose to continue our spectroscopic identification program in the spring sky with MMT. We have selected 43 candidates with $20 < i < 20.5$ and photometric redshift between 5.1-5.7, which are too faint to be observed with any telescope in China. Our new quasar sample will provide key probes to the post-reionization IGM, and accurately determination the quasar black hole mass function and luminosity function at $z >5$. We request two dark/grey nights for the MMT/Red Channel observations of these 43 candidates.

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	dark/grey	March	Feb-Apr	yes	yes
or:											
1a										no	no

Scheduling constraints and unusable dates *(up to 4 lines)*:

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	J100743.27-015942.7	10:07:43.27	-01:59:42.7	i=20.49, z=20.09, photoz=5.37
2	J110011.67+164248.3	11:00:11.67	+16:42:48.3	i=20.31, z=19.74, photoz=5.35
3	J110357.60-183308.7	11:03:57.60	-18:33:08.7	i=20.17, z=19.36, photoz=5.27
4	J110935.56+343755.4	11:09:35.56	+34:37:55.4	i=20.1, z=19.27, photoz=5.29
5	J123617.52+371855.5	12:36:17.52	+37:18:55.5	i=20.44, z=19.54, photoz=5.65
6	J124303.78-001256.9	12:43:03.78	-00:12:56.9	i=20.31, z=19.48, photoz=5.19
7	J130212.35+014936.0	13:02:12.35	+01:49:36.0	i=20.46, z=19.5, photoz=5.23
8	J135628.79+582757.6	13:56:28.79	+58:27:57.6	i=20.18, z=19.42, photoz=5.31
9	J141122.49+180241.9	14:11:22.49	+18:02:41.9	i=20.45, z=19.66, photoz=5.35
10	J142039.49+253004.9	14:20:39.49	+25:30:04.9	i=20.17, z=19.36, photoz=5.65
11	J142359.06-210624.9	14:23:59.06	-21:06:24.9	i=20.15, z=19.29, photoz=5.29
12	J142731.33+141840.4	14:27:31.33	+14:18:40.4	i=20.32, z=19.94, photoz=5.38
13	J145055.49+371351.1	14:50:55.49	+37:13:51.1	i=20.32, z=19.79, photoz=5.34
14	J153313.06+060306.4	15:33:13.06	+06:03:06.4	i=20.39, z=19.57, photoz=5.35
15	J154957.32-171916.2	15:49:57.32	-17:19:16.2	i=20.45, z=19.53, photoz=5.25
16	J155848.26+562556.5	15:58:48.26	+56:25:56.5	i=20.35, z=19.43, photoz=5.31
17	J160506.97-003628.5	16:05:06.97	-00:36:28.5	i=20.26, z=19.38, photoz=5.22
18	J161930.76+090347.7	16:19:30.76	+09:03:47.7	i=20.49, z=19.9, photoz=5.34
19	J163057.19-101231.5	16:30:57.19	-10:12:31.5	i=20.41, z=19.28, photoz=5.26
20	J164330.84+133412.0	16:43:30.84	+13:34:12.0	i=20.02, z=19.28, photoz=5.25
21	J164744.81+372128.6	16:47:44.81	+37:21:28.6	i=20.36, z=19.78, photoz=5.32
22	J165858.03-035014.8	16:58:58.03	-03:50:14.8	i=20.33, z=19.55, photoz=5.28
23	J171352.60+212714.5	17:13:52.60	+21:27:14.5	i=20.37, z=19.57, photoz=5.25
24	J172022.56-011216.2	17:20:22.56	-01:12:16.2	i=20.0, z=19.17, photoz=5.27
25	J172936.98+430425.4	17:29:36.98	+43:04:25.4	i=20.44, z=19.61, photoz=5.33
26	J175112.09+241409.2	17:51:12.09	+24:14:09.2	i=20.32, z=19.46, photoz=5.17

If this program uses a PI instrument, attach the approval email from the PI to this proposal.

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page.)*

Student's Name	Advisor's Name	Thesis
Jinyi Yang	Xuebing Wu	yes
Feige Wang	Xiaohui Fan, Xuebing Wu	no
Qian Yang	Xuebing Wu	no

Scientific Justification *Please include overall significance to astronomy and significance within the proposal's discipline. Limit text to one page, with a maximum of two additional pages for figures, captions, and references.*

High redshift quasars are important tracers to study the structure and evolution in the early Universe, while they are very rare, especially for the redshift range $5.1 < z < 5.7$. A factor of 2 greater decrease in the number density of luminous quasars from z=5 to 6 than from z=4 to 5 was claimed (McGreer et al. 2013). Although more than 180,000 quasars are known, only $\sim$150 quasars at $z > 5$. There is an obvious gap of known quasars at $5.1 < z < 5.7$ (See Fig.1), which is because their similar optical colors with late-type stars. However, this redshift range is one of the most important epoch of IGM evolution, black hole growth and quasar evolution in the early universe.

Observations of Gunn-Peterson effects using absorption spectra of quasars at $z \gtrsim 5.7$ have established the redshift $z \sim 6$ 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 remain largely uncertainty. Recent work indicates that the tail of reionization extends to significantly lower redshift, and might have only fully completed by $z \sim 5$ (Becker et al.2014). 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 IGM temperature, photon mean free math, metallicity and the impact of helium reionization (e.g. Bolton et al 2012). They place strong constraints on models of reionization topology as well as on the sources of reionization and chemical feedback by early galaxy population. Lyα opacity measurement can directly show the evolution of IGM. Following Fan et al. (2006), several new measurement about the Lyα opacity at $5 < z < 6$ are given (Simpson et al. 2014; Becker et al. 2014) but still can not constrain the scattered region at $z > 5$ (Becker et al. 2014). To measure the Lyα opacity, absorption lines and near-zone shown in the spectra of high z quasars always be used. Therefore, quasars at $5 < z < 6$ provide crucial probes to the IGM during the post-reionization epoch. However, the lack of known luminous quasars at $z \sim$ 5.1 - 5.7 is now a significant limiting factor to understanding this key era.

In addition, quasars at this redshift range is a key point for quasar luminosity function(QLF) and black hole mass function(BHMF). From the previous large area quasar surveys and smaller area deep surveys, QLFs have been obtained for quasars at $z < 2.2$ (Fan et al. 2001;Croom et al. 2009), $2.2 < z < 3.5$ (Ross et al. 2012; Palanque-Delabrouille et al. 2013), $4.7 < z < 5.1$ (McGreer et al. 2013), $z \sim 6$ (Jiang et al. 2009; Willott et al. 2010). However, QLF at 5.1 < z < 5.7 is still unclear because of the limited sample size. Thus, finding more quasars at $z > 5.1$ will help us to calculate QLF, and constrain the slope and evolution model. BHMF is an important tool for understanding the black hole accretion and growth, the co-evolution between supermassive black holes (SMBH) and their hosts. Combining with the black hole-stellar mass relation at low redshift, Willott et al (2010) suggests that there is a rapid black hole mass growth phase after $z \sim 6$. Study of black hole growth at $z \sim 4.8$ and low redshift quasars shows that there is a probably fast SMBH growth at redshift $z \sim 4.8$, probably the very first such phase for most SMBH (Trakhtenbrot et al. 2011. See Fig. 2). So how the black holes evolve and begin their rapid growth at $5 < z < 6$ are key questions. But due to less quasars at $z \gtrsim 5$, we do not know the accurate beginning time of this fast growth phase.

In the past several years, we have developed methods to use optical/near-IR colors to discover quasars at intermediate redshifts and with redshifts up to 5 (Wu & Jia 2010; Wu et al. 2011,2012,2013). We proposed two quasar selection criteria: SDSS-UKIDSS $YKgz$ & $JKiY$ colors for quasars at redshift $4.2 < z < 5.7$; SDSS-WISE riz & $W1 - W2$ colors for quasars at redshift $z > 4.8$(Fig. 3). We have made some efforts to identify some bright candidates ($i < 20.0$) with the Lijiang 2.4m telescope and found 46 z > 4.5 quasars with 19 at $5.1 < z < 6$. We will spectroscopically identify 23 faint candidates in this December on MMT/Red through TAP 2014B. We select other 43 candidates with $20 < i < 20.5$ and photometric redshifts between 5.1 and 5.7, and propose to identify them still with MMT/Red. We also get several nights on ANU and Bok telescopes for our brighter candidates. But the faint part can not be observed using any telescope in China or ANU and Bok. MMT Red channel spectrograph is the best choice for these 43 candidates. We believe that these observations will definitely lead to the discovery of a few $z > 5.1$ quasars and provide an important test on the effectiveness of our proposed method for finding $z > 5$ quasars. Based on these results, we will construct a new significantly large sample of $z > 5.1$ quasars to study the possible evolutions of QLF and quasar properties from redshift 5 to 6, and to understand post-reionization IGM conditions.

References

Becker G. D. et al., 2014, arXiv:1407.4850
Bolton, J.S. et al., 2012, MNRAS, 419, 2880
Croom, S.M. et al., 2009, MNRAS, 399, 1755
Fan, X. et al., 2001, AJ, 121, 54
Fan, X., Carilli, C.L., Keating, B. 2006, ARA&A, 44, 415
Jiang, L. et al., 2009, AJ, 138, 305
McGreer, I. et al., 2013, ApJ, 768, 105
Palanque-Delabrouille, N. et al. 2013, A&A, 551, A29
Richards, G.T. et al., 2006, AJ, 131, 2766
Ross, N.P. et al., 2012, ApJS, 199, 3
Simpson, C. et al., 2014, MNRAS, 442, 3454
Trakhtenbrot, B. et al., 2011, ApJ, 730, 7
Willott, C.J. et al., 2010, AJ, 140, 546
Wu, X.-B., & Jia, Z., 2010, MNRAS, 406, 1583
Wu, X.-B. et al., 2011, AJ, 142, 78
Wu, X.-B. et al., 2012, RAA, 12, 1185
Wu, X.-B. et al., 2013, AJ, 146, 100

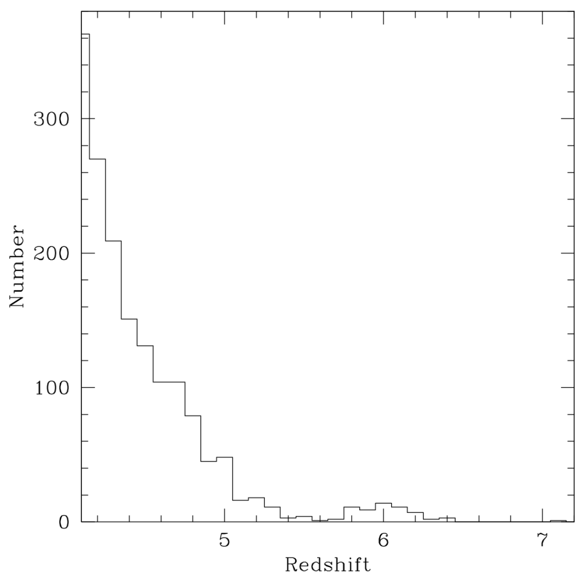

Figure 1: The distribution of known quasars at redshift $z > 4.1$. There is an obvious gap at $5.1 < z < 5.7$. The number of quasars at $5 < z < 6$ is significantly lower than it at lower redshift range.

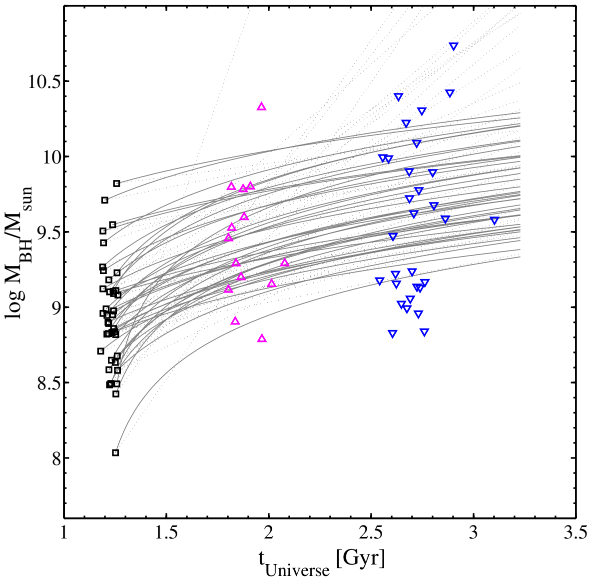

Figure 2: Black hole growth in quasars from redshift ~ 4.8 (black) to ~ 3.3 (pink) and ~ 2.4 (blue), adapted from Trakhtenbrot et al. 2011. The comparison between z $\sim$ 4.8 quasars and low redshift quasars shows that there is an epoch of fast SMBH growth, probably the very first such phase for most SMBHs at z $\sim$ 4.8. However, due to less quasars discovered at redshift between $\sim$ 4.8 to $\sim$ 6, we cannot identify the accurate beginning time of the fast growth phase. Our program is expected to discover more quasars at this redshift and the future follow up near-IR observations on these new quasars will finally address this question.

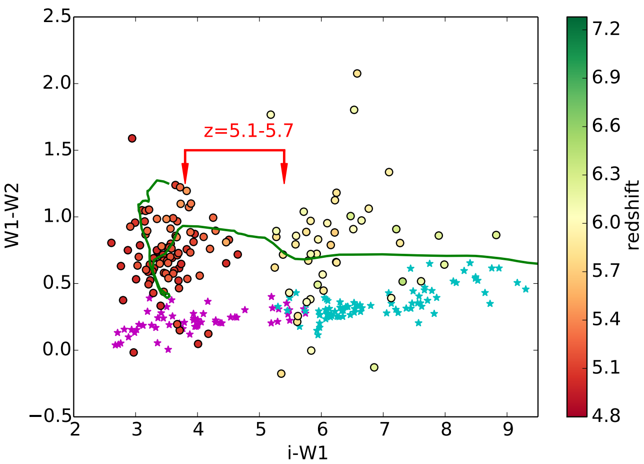

Figure 3: The SDSS-WISE color-color selection we used for quasars at $5.1 < z < 5.7$. The purple stars denote M dwarfs, the cyan stars denote L dwarfs. The color cycles denote known $z > 4.8$ quasars and the color bar is redshift. The green line is a color color track calculated from a $z \sim 5$ composite spectrum. The red arrows label the position of $5.1 < z < 5.7$ quasars in W1-W2/i-W1 color color space. From this plot, we can see that quasars at $5.1 < z < 5.7$ can be separated from stars well.

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? Justify sample size, instrument choice, signal-to-noise, exposure times, and lunar phase. Also briefly explain plans for data reduction, and what expertise or effort each team member will contribute to the project. (**up to one page**)*

Target selection: We selected our quasar candidates from SDSS-UKIDSS and SDSS-ALLWISE. We have developed methods to use optical/near-IR colors to discover quasars at intermediate redshifts and with redshifts up to 5 (Wu & Jia 2010; Wu et al. 2011,2012,2013). Using the samples of spectroscopically identified quasars and stars with SDSS, UKIDSS and WISE photometric data, we proposed two quasar selection criteria: SDSS-UKIDSS $YKgz$ & $JKiY$ color-color diagram for quasars at redshift $4.2 < z < 5.7$; SDSS-WISE riz & $W1 - W2$ colors for quasars at redshift $z > 4.8$. For these candidates selection, We started from two catalogs of high-redshift quasar candidates selected from SDSS based on two different methods (extreme deconvolution & k-nearest neighbor), and selected only pointed sources with relatively clean SDSS photometry by considering many different photometric flags. We then cross-matched them with the UKIDSS/LAS DR9 and ALLWISE data. We selected sources with SDSS-UKIDSS colors and SDSS-ALLWISE colours separately and deleted targets with SED shape with large differences from that of quasar composite SED. We then limit the photometric redshifts between 5.1 and 5.7. After deleting known quasars and considering objects with RA between 10h and 18h, we chose 43 quasar candidates with i-band magnitudes between 20.0 and 20.5. According to the efficiency of finding brighter $z > 5$ quasars ($i < 20.0$) from Chinese 2.16m and 2.4m telescope, we expect that the MMT/Red will identify at least half of them to be real $z > 5.1$ quasars. Combining with pervious discovered quasars and the result of MMT/Red in this December, this spectroscopy will substantially increase the number of quasars at $5.1 < z < 5.7$, and help us to construct a large quasar sample within the whole SDSS-UKIDSS/WISE area for studying the quasar luminosity function, the evolutions of quasar properties and IGM from redshift 5 to redshift 6.

Configuration and exposure time: We propose to use MMT Red channel spectrograph to do spectroscopic identifications of 43 high redshift quasar candidates with photometric redshifts between 5.1 and 5.7. At redshift higher than 5.1, the strongest emission line of quasars, Lyman-α line (with rest-frame wavelength of 1216 $\mathring{A}$), will move beyond 7400 $\mathring{A}$. Therefore, MMT Red channel, especially with the grating 270 lines/mm which blazes at 7300 $\mathring{A}$ and have a resolution about 11.4 $\mathring{A}$ and a broad wavelength coverage about 3705 $\mathring{A}$, is perfect for our purpose. In order to address whether these candidates are real quasars, we need the signal-to-noise $\sim 5\ \sigma$ per resolution element. The i-band magnitudes of our 43 targets are in the range of 20.0 to 20.5, we require the exposure time for each target around 20 - 30 minutes at the typical seeing of 1.2". Considering about 5 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 needed is about 20 hours. Therefore, we request 2 dark/grey nights for MMT Red channel spectrograph observations of these 43 high redshift quasar candidates.

Lunar phases: As possible $z > 5.1$ quasars, our targets are faint in the whole optical window and much fainter in the wavelength shorter that $7000\mathring{A}$. The moon light will affect our spectroscopy significantly. We have to so such observations in dark and grey nights to ensure the quality of the spectra.

Data plan: All of our team members are working on the spectroscopy study of quasars. The observations with the MMT Redchannel spectrograph and data reductions will be carried out by Jinyi Yang, and Feige Wang. Xiaohui Fan and Xue-Bing Wu are experts on quasar studies and are very much experienced in optical/near-IR spectroscopy. Qian Yang and Xiaoyi Dong will also provide helps in the data analysis. The data will be available to any interested people in China and international community upon a request by email.

TAP Usage and Context *The TAC needs to understand the scope of this project — (1) How many total TAP nights are you requesting this semester, including any CFHT time from a linked proposal, and if more time will be necessary in future semesters, how many nights will you need to complete the project (best guess)?; (2) If a substantial amount of observing for this project comes from non-TAP telescopes, tell us about that observing, and how the TAP part fits in; (3) If you are collaborating with people who have access to other telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how TAP time and your participation fit in. 4) Please explain the ways in which this program would help fulfill the goals of the Telescope Access Program. (**up to one page**)*

We request 2 dark/grey nights for the MMT Red channel spectrograph observations of 43 high redshift quasar candidates with i-band magnitude between 20 and 20.5. We are working on constructing a large $z > 5.0$ quasar sample with Chinese 2.16m and 2.4m telescopes, possible TAP program we proposed, ANU and Bok telescope. Because using the telescopes 2.16m, 2.4m, ANU and Bok we can only observe bright targets (with i-band magnitude brighter than $\sim$ 20), we definitely need some observation time on MMT from TAP program. The whole program could finally spectroscopically identify several tens z >5.1 quasars, which could be the largest quasar sample at this redshift range. With these new quasars, we will be able to study the luminosity function, black hole mass function and IGM properties from redshift 5 to redshift 6.

This proposal is the second one focusing on finding $z >$ 5.1 quasars. We have proposed 1.5 nights on MMT Red channel spectrograph through TAP 2014B. The observation will be took in this December. We will spectroscopically identify 23 candidates within RA $\sim$ 0h-9h in this run, and expect to confirm other candidates within RA $\sim$ 10h-18h in 2015A. We also get several nights with ANU and Bok for the bright part of our quasar candidates. These observations will help us to complete the construction of our $z >$ 5.1 quasars sample.

By using MMT Red channel spectrograph to find high-redshift quasars, three graduate students in our team will gain important experiences in doing spectroscopy with a large and advanced telescope in the world. Combining with our efforts in using the Chinese 2.16m, 2.4m, ANU and Bok telescopes in finding bright $z \sim$ 5 quasars, this will form a substantial part of the PhD thesis study of Jinyi Yang and Qian Yang at Peking University, which will focus on the construction of a relatively complete sample of $z >$ 5 quasars and study the quasar luminosity function and evolution.

Previous Use of TAP Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through TAP 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**)*

I have got 1.5 nights on MMT/Red through TAP 2014B and will take the spectroscopic confirmation in Dec 2014. This run will help us to identify a part of our candidates as quasars at z >5.1.

One of the Co-Is (X. Wu) has led four successful TAP runs in the last 3 years. The Palomar Hale Triplespec observations on 30 quasars in 2011B and 2012A have led to a paper (Zuo et al. 2014) which is under the third round of review of ApJ. The CFHT WIRCam Y-band imaging in 2012B has helped us to select additional quasars and galaxy candidates in a two-degree VVDS/F22 field and the subsequent MMT Hectospec spectroscopy in 2013B has led to the discovery of 27 new quasars with 17.5 $< i <$ 22.5 at 0.67 $< z <$ 4.2 and about 100 galaxies in an one-degree field. Two papers related to these two observations are in good progress.

One of the Co-Is (F. Wang) has got 2 nights from P200/Triplespec in March (18th-19th) 2014 through TAP 2014A term. That program is aimed to study the black hole mass of high redshift BAL quasars. Due to the bad weather, we observed some bright $z \sim 5$ quasars discovered by us recently instead of some faint BAL quasars proposed before. Finally, we got seven Triplespec Near-IR spectra for three high redshift quasars and four weak lines quasars. We also got 1 night from Magellan/FIRE from TAP 2014B on Oct 4th and Feige Wang will go there for observation.