OBSERVING REQUEST
University of Arizona Observatories

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

Probing Black Hole Growth in the Earliest Luminous Quasars: Beyond SDSS

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Abstract of Scientific Justification

We propose to carry out near-IR spectroscopy of a sample of eight newly discovered quasars at $z \sim 6$ using Magellan/FIRE. These new quasars are selected from near-IR based sky surveys, including UKIDSS, VIKING and Pan-STARRS1, both reaching higher redshift and higher survey completeness compared to pure optical survey such as the SDSS. FIRE spectra will provide continuous spectra coverage from 1 to 2.5 microns, sampling the crucial spectral region including CIV to MgII and FeII emissions, and allow us to measure the central black hole (BH) masses and metallicity of quasars. This is part of our larger effort to probe quasar/BH properties in the largest possible luminosity-BH mass parameter space at high redshift. Using this new sample, we will be able to derive the mass function and accretion rate distributions of active supermassive BHs in the earliest epoch. The BH distribution, combined with our on-going survey of star formation activities in the quasar host galaxies using submm and radio data, will reveal the relationship between BH growth and galaxy assembly in early epoch at the end of cosmic reionization, and place strong constraints on BH and galaxy formation theories. In addition, the near-IR spectra will be used to measure unbiased quasar redshifts which are needed for radio CO detections and studies of cosmic HII regions, and to measure the metallicity of quasar broad line regions in order to constrain the chemical enrichment history in the vicinity of the highest redshift quasars.

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	MAG1		FIRE			2	bright	Feb - Apr	Feb - May	yes	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	J0421-2657	04:21:38.05	-26:57:15.6	z=5.96, y_{AB} = 19.6
2	J1148+0702	11:48:03.29	+07:02:08.3	z=6.29, y_{AB} = 20.4
3	J1152+0055	11:52:21.27	+00:55:36.7	z=6.34, y_{AB} = 21.5
4	J1207+0630	12:07:37.44	+06:30:10.4	z=6.04, y_{AB} = 20.2
5	J1215+0023	12:15:16.88	+00:23:24.7	z=5.93, y_{AB} = 21.5
6	J1229+0419	12:20:13.21	+04:19:27.7	z=5.89, y_{AB} = 21.1
7	J1243+2529	12:43:40.81	+25:29:23.9	z=5.83, y_{AB} = 20.6
8	J1403-1200	14:03:29.33	-12:00:34.1	z=5.84, y_{AB} = 20.7

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

Luminous quasars are discovered at redshift up to 7.1 (Fan et al. 2003, Willott et al. 2007, Mortlock et al. 2011, Venemans et al. 2013). Detections of such objects indicates the existence of billion $M_\odot$ black holes (BHs) merely a few hundred Myrs after the first star formation in the Universe. They are surrounded by metal-enriched gas and young galaxies with intense star formation. The absorption line spectra of the highest redshift quasars reveal complete Gunn-Peterson absorption, marking the end of the reionization epoch at $z \sim 6$ (e.g. Fan et al. 2006a).

Searches for reionization-era quasars started from pure optical selection, using deep, wide-field optical survey data, including SDSS-main survey (Fan et al. 2006b), SDSS-deep stripe (Jiang et al. 2009) and CFHQS (Williott et al. 2010). In the last few years, significant progress in large area near-IR surveys has enabled another quantum leap in high-redshift quasar search; the inclusion of near-IR data, including UKIDSS (YHJK bands, Mortlock et al. 2010), VIKING (YHJK bands, Venemans et al. 2014), Pan-STARRS1 (Y band, Banados et al. 2014) and WISE (W1 and W2 bands, Wu et al. 2014), allows us to not only reach higher redshift ($z > 6.5$), but also greatly improve the completion of quasar selection at $z \sim 6$ range. Figure 1 summarizes the current status of quasar surveys at $z \gtrsim 6$; the majority of the objects begins to come from near-IR-based surveys. We have started a large collaborative effort to systematically follow up these newly discovered quasars in wavelength from near-IR to submm and radio. In particular, the extended redshift range and completeness of the new quasars provide a fundamental sample to study the BH activity and its relation to early galaxy formation. One of the most important component of these observations is the rest-frame UV spectra which contain strong diagnostic emission lines, providing key information on the physical conditions and emission mechanisms of the broad emission line region and the only means to measure BH masses at high-redshift At $z \sim 6$, measurement of these spectral lines is difficult, as the rest-frame UV waveband is redshifted to the near-IR range.

In 2015A, we propose to use Magellan/FIRE to obtain high quality near-IR spectra of eight quasars at $z \gtrsim 6$. The Magellan spectra will allow us to use the CIV and MgII emission line to measure the BH masses in those systems and to determine the active BH mass function and BH accretion rate distribution at z $\sim$ 6. These observations will be combined with existing near-IR spectroscopy of SDSS quasars. They will allow us to study:

1. Quasar BH Mass at $z \sim 6$. For high-redshift quasars, black hole masses can only be estimated using mass scaling relations based on broad emission line widths and continuum luminosities. Width of strong emission lines are used as the characteristic gravitational velocity to determine black hole masses (e.g. McLure et al. 2004, Vestergaard & Peterson 2006). Hβ is redshifted out of the near-IR range for $z > 6$ quasars. MgII provides the best estimator of black hole masses. We will fit the K-band spectra to derive the MgII line width, using the best UV FeII template (Vestergaard and Wilkes 2001) to subtract FeII emission, and combining broad band photometry for accurate continuum determination. Our J-band spectra will cover the CIV line which provides an independent BH mass measurement. The observations will allow us to measure BH masses for all quasars in the sample.

2. Eddington Ratio and Accretion Rate Distribution. Figure 2 shows the BH masses and Eddington ratios of SDSS quasars that we have observed so far. We found that their average BH mass is of the order $10^9 M_\odot$, with an average Eddington ratio of ~ 1 and a scatter of a factor of 3 (Figure 2, de Rosa et al, 2011). This is a highly significant result: BHs at $z \sim 6$ are accreting and shining at the maximum rate, a factor of $\sim 3-4$ higher than those with similar luminosity at $z \sim 2-4$. It places the strongest limit yet on the model of BH seed and growth: the Universe was only 20-30 Eddington times old at $z \sim 6$, BHs need to accrete at or close to the maximum Eddington rate in order to grow from a stellar seed BH to 10^9 M$_\odot$ by $z \sim 6$. BH mass measurement of our complete sample will allow us to derive the distribution of quasar Eddington ratio and accretion rate in this early epoch.

3. BH Mass Function. Vestergaard et al. (2008) presented the first determination of active BH mass function using the SDSS main quasar sample at $z < 5$. We (Kelly, Vestergaard & Fan 2009) have developed a new Bayesian-based technique to derive the underlying BH mass function in the presence of flux limit and color selection effect, while correcting for biases introduced by BH mass measurement uncertainties. We will use this new technique to derive the BH mass function at $z \sim 6$. The mass function and Eddington ratio distribution will be compared in detail with theoretical models of early BH growth and assembly (e.g., Li et al. 2007) through our on-going collaborations.

4. Relation between BH Growth and Galaxy Assembly. Submm/radio observations of $z \sim 6$ quasar sample probe star formation activities in the host galaxies (e.g Wang et al. 2013). The submm continuum provides an estimate of star formation rate, assuming dust heating from star formation, while molecular line measurements such as CO and [CII] in the radio (Walter et al. 2009) measures ISM properties, and more importantly, gas kinematics in galaxy centers. Although there are still uncertainties in its interpretation, the radio data, when combined with our new BH mass measurement, directly probe of BH/galaxy co-evolution in early epoch. As models (Narayanan et al. 2008) and data improve, they will provide the first measurement of the evolution of the relationship of BH mass and galaxy mass at the earliest epoch.

Additional Science Goals

Accurate measurements of the systematic redshift of the quasars. High ionization lines such as CIV and SiIV are known to have large velocity offset from the systematic redshift of the quasar; Lyα is strongly affected by IGM absorption. MgII emission provide the best unbiased redshift determination of the quasar. This is important for both CO line detections in the ratio (due to limited bandwidth of radio receivers) and for determining the sizes of cosmic HII regions around quasars which is a potentially powerful probe to reionization.

Chemical abundances and the FeII/MgII ratios. Photoionization models show that various emission-line ratios provide reliable estimates of metallicity in the BLRs of quasars. We will use line ratios such as NV/CIV to measure the metallicity of broad line region. In addition, Fe abundance is of particular interest: most of the Fe in the solar neighborhood is generated by Type Ia supernovae (SNe Ia), whose precursors are believed to be long-lived intermediate-mass stars in close binaries, so appreciable Fe enrichment can only happen on a timescale of one Gyr after the initial starburst. Metallicity measurements will directly constrain the chemical enrichment history in the early quasar host galaxies (de Rosa et al. 2011).

Reference.

Banados et al. 2014, AJ, 148, 14
de Rosa et al. 2011, ApJ, 739, 56
Fan, et al. 2003, AJ, 125, 1649
Fan, et al. 2006a, ARAA, 44, 415
Fan, et al. 2006b, AJ, 132, 117
Jiang, et al. 2007, AJ, 134, 1150
Jiang, et al. 2009, AJ,138, 305
Kelly et al. 2009, ApJ, 392, 1388
Kurk, et al. 2007, ApJ, 669, 32
Kurk, et al., 2009, ApJ, 702, 833
Li, et al. 2007, ApJ, 665, 187
McLure, et al. 2004, MNRAS, 352, 1390
Mortlock et al. 2011, Nature, 474, 616
Narayanan , et al. 2008, ApJS, 174, 13
Venemans et al. 2013, ApJ, 779, 24
Vestergaard & Wilkes 2001, ApJS, 134, 1
Vestergaard & Peterson 2006, ApJ, 641, 689
Vestergaard, et al. 2008, ApJ, 674, L1
Walter, et al. 2009, Nature, 257, 699
Wang et al. 2013, ApJ, 773, 44
Willott, et al. 2007, AJ, 134, 2435 Willott et al. 2010, AJ, 140, 546
Wu et al. 2014, Nature, submitted
Yi et al. 2014, ApJL, submitted

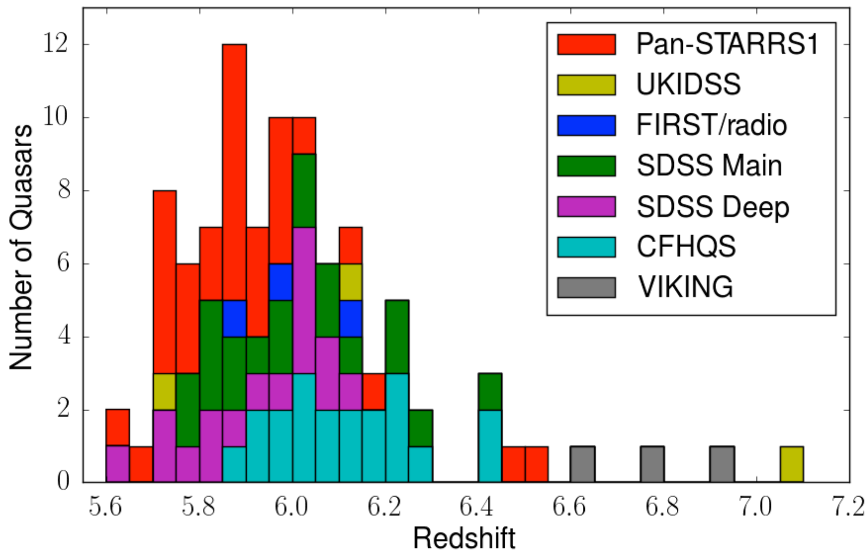

Figure 1: Total number of known quasars as a function of redshift at $z > 5.5$. Early discoveries are dominated by pure optical surveys such as SDSS and CFHQS; recently discoveries using near-IR surveys, including UKIDSS, VIKING and Pan-STARRS1 have pushed the highest quasar redshift to $z > 7$, begun to establish a sizable sample at $z > 6.3$ and greatly improved survey completeness at $z \sim 6$.

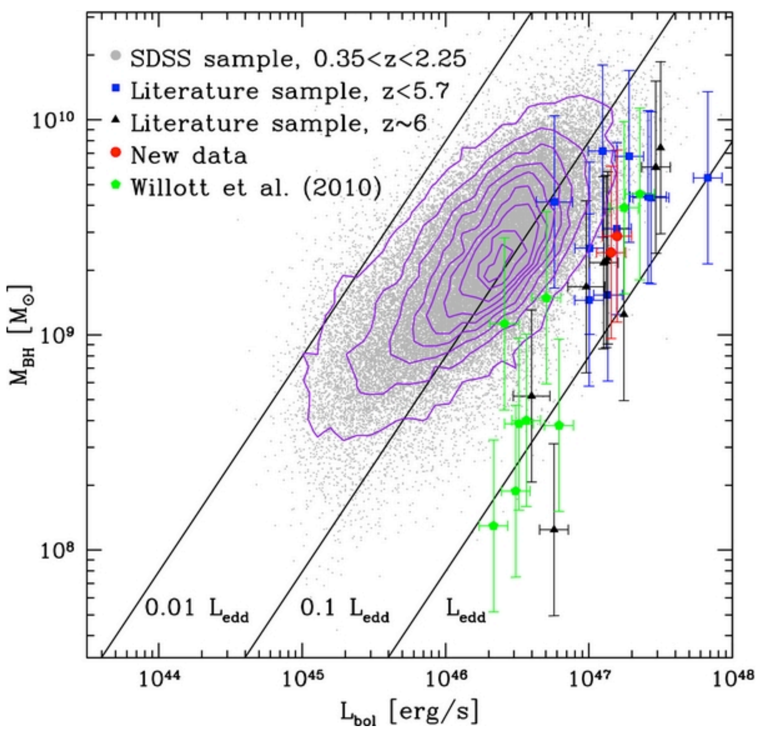

Figure 2: Distribution of quasar BH masses vs. quasar luminosity. The small points are measurements of ~ 60000 quasars from the SDSS main sample. The large red points with error bars are the current $z \sim 6$ sample. We have also shown the locations at which the quasar Eddington ratio is 1, 0.1 and 0.01. The $z \sim 6$ quasars are accreting at the maximum Eddington rate, which is a factor of $3 - 4$ higher than the average at low redshift. From de Rosa et al. (2011).

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**)*

Sample Selection

Our goal is to measure BH masses and metallicities of a large, complete quasars at $z \gtrsim 6$, selected from near-IR sky surveys. In this proposal, we will use FIRE spectrograph on Magellan to target eight new quasars in the spring sky. These objects were discovered by near-IR surveys (Pan-STARRS: 3; UKIDSS: 3; VIKING:2). They have redshift ranging from $z \sim 5.8$ to 6.3 and y_{AB} magnitude between 19.6 and 21.5.

Instrument and Configuration

The Folded-port InfraRed Echellette (FIRE) spectrograph, in is Echellette mode, provides a continuous 0.9 - 2.5 micron coverage at $R \sim 6000$ with high throughput. Our FIRE will cover the rest-frame 1300Å to 3000Å for quasars at $z \sim 6$. This spectral region contains important spectra lines, including SiiIV, CIV, MgII and FeII complex, that are needed for BH mass and metallicity measurements in quasars. In addition, the resolution of FIRE is sufficiently high that we are effectively resolving OH lines in the sky, providing better sky subtraction and higher observing efficiency, even with the additional dispersion element. It is the ideal instrument for our study.

Exposure Time

In order to measure the CIV and MgII line width (average ~ 4000 km/s), we will need to bin the data to about 500 km/s/pixel resolution, or $R \sim 600$. Our previous experience shows that a S/N of 5 – 7 on the continuum is usually sufficient not only measure the line, but also fit FeII templates to the data. Our targets have K magnitude ranging from $K = 17.5$ to 19.5. Based on our previous FIRE observations, we will need ~ 30 min exposure time for objects at $K < 18$, ~ 1 hour exposure for $K = 18 - 19$ and 3 hour exposure for $K > 19$. For all eight targets, we need a total integration time of 14.5 hours. Assuming a 30% overhead for set-up, offsetting and standard calibrations, we request about 19 hours, or two nights of observing time. The best time for observing is from Feb - Apr. We can use relatively bright time, but full moon will affect our data at the shortest wavelength, so should be avoided if possible.

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**)*

This proposal is part of a larger program of carrying out near-IR spectroscopy of newly discovered $z \gtrsim 6$ quasars discovered in near-IR surveys. In the past, we have used Gemini, VLT, Keck and Magellan/FIRE to observe the optically-selected SDSS sample. They have been published in Jiang et al. (2007) and Kurk et al. (2007, 2009), de Rosa et al. (2011), Simcoe et al. (2012), Yi et al. (2014), and Wu et al. (2014). This is a natural extension of our previous FIRE programs. In addition to the Arizona group's effort, R. Simcoe (MIT) is using FIRE to target the brightest objects in our sample for IGM studies, and our MPIA collaborators are using VLT/X-shooter to target the rest of the sample.

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)***

In past two years. Fan is PI of the following programs:

- 2014B: two nights on MMT/MAESTRO for quasar IGM spectroscopy. Instrument throughput issue. Data are useful for engineering only.
- ⋆ 2014A: two nights on Magellan/FIRE for $z \sim 5$ quasar follow-up. One paper published, one ready to submit.
- 2014B etc. ToO proposal for high-redshift GRBs on LBT, no triggers yet.
- ⋆ 2013B: three nights on MMT for PS1 quasar follow-up. Eight new PS1 quasars at $z \sim 6$. One paper published,two more in preparation.
- 2013B, 15 nights on Bok for deep u-band imaging for SDSS-IV target selection, observations completed. Data reduction finished and incorporated into SDSS target selection. Data will be released with all SCUSS data. Several papers already published by SCUSS team (including X. Fan).
- 2013A, 2012AB, six nights on LBT/LUCI for $z \sim 7$ galaxy spectroscopy. One paper published, one paper submitted.