OBSERVING REQUEST
University of Arizona Observatories

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

Bright $z \sim 6$–7 Quasars from Pan-STARRS

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Abstract of Scientific Justification

We propose to obtain follow-up MMT/Red spectroscopy of $z > 6$ quasar candidates selected from Pan-STARRS1 (PS1) data. PS1 includes y-band imaging and has the potential to uncover quasars at $z > 6.5$, advancing studies of the earliest quasars further back into the epoch of reionization. Studies of SDSS quasars at $z \sim 6$ have shown that they are already powered by $10^9 M_\odot$ black holes and surrounded by metal-rich gas. Thus we must push to even higher redshifts to find the first generation of quasars and better understand the evolution of the quasar population in the early universe. PS1 is the best survey currently in operation for bright high-z quasar searches, and has covered the entire Spring sky visible in the Northern hemisphere to an unprecedented depth in the reddest optical bands, an area largely untapped by previous surveys. Pan-STARRS has now covered the full 3π footprint with multiple epochs in each bandpass and is generating stacked images that are much more reliable for quasar candidate selection than the previous single-epoch imaging. The result is a new set of highly promising quasar candidates at $z \gtrsim 6$ needing spectroscopic confirmation. Pan-STARRS probes the brightest quasars on the sky, which are ideal for multi-wavelength follow-up, IGM studies, and exploration of the first massive systems to form in the early universe.

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	f/9	Red			3	gray	Mar–May	Feb–Jun	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: March or later is optimal given the sky coverage of PS1 accessible to MMT.

no text past this line

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	PS1 QSO candidates	full Northern sky		

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 at high redshift provide direct probes of the evolution of supermassive black holes (BHs) and the intergalactic medium (IGM) at early cosmic time. Over the last decade, numerous studies have established a sample of $\sim$60 luminous quasars at $5.5 < z < 6.5$, the largest fraction of which were selected using data from the Sloan Digital Sky Survey (SDSS; Fan et al. 2001,03,04,06). Main results emerging from the studies of these quasars (see also Kurk et al. 2007, Willott et al. 2010, De Rosa et al. 2011) include:

• Billion $M_{\odot}$ BHs are already in place less than a Gyr after the Big Bang.

• Complete Gunn-Peterson absorption indicates a rapid increase in the IGM neutral fraction.

• Broad lines emitted in the proximity of the black holes show metal abundances consistent with what observed at low redshift.

• Strömgren radii of the volume photoionized by the quasar are of few Mpc, corresponding to a minimum activity time of the quasars of 1–20 million years (e.g., Kurk et al. 2007; see also Haiman & Cen 2002).

• Quasar host galaxies at z>6 are intensely forming stars (e.g., Walter et al. 2009; Venemans et al. 2012).

These key findings strongly suggest that crucial changes are happening at z$\sim$6–7, about one billion years after the Big Bang. This is consistent with recent results on the evolution of star-forming galaxies at similar redshift (e.g. Yan & Windhorst 2004, Castellano et al. 2010, Labbé et al. 2010,12, Bouwens et al. 2010,11). **These results also point to the need to push to the new frontier at z>7, which might reveal dramatic changes in the properties of BHs and of the IGM.**

Although surveys such as the SDSS have been highly successful in finding quasars at z$\sim$6, they have a redshift limit of z$\approx$6.5 due to the lacking sensitivity at > 9000 Å (see also Fig. 1). Indeed, *currently only one quasar at z>6.5 is reported in the literature* (Mortlock et al. 2011).

A new era in high-z quasar searches: The **Panoramic Survey Telescope & Rapid Response System** (Pan-STARRS, PS1) is successfully surveying 3/4 of the sky in $grizy$. PS1 represents a fundamental step forward in high-z quasar searches for three reasons: 1) It has already covered three times the area observed with the SDSS; 2) It goes significantly deeper, especially in the reddest bands (where high-z quasars are detected); 3) Most importantly, thanks to the y-band filter, it opens up a new redshift window, allowing the search for z drop-outs (i.e., sources with 6.5<z<7.5). **In early 2013, PS1 delivered its first, 3π stacked catalogues**, thus marking a transformational leap forwards in terms of depth and purity: By December 2012 we had only 2 QSOs discovered based on PS1 data (one of them presented in Morganson et al. 2012); only 9 months later the count reached 9 confirmed PS1 QSOs at z$\sim$6 (Bañados et al. 2013; see Fig. 1).

Selecting high-z quasar candidates: Quasars at z>5.5 are expected to show virtually no emission in i (z$\sim$6) and z (z$\sim$7), and relatively bright continua in the y and J bands. The y-J color ranges between -0.5 and +0.5, according to the actual redshift, to the equivalent width of Lyα and other bright emission lines, and to the slope of the power-law continuum. On the other hand, brown dwarfs (which represent the main contaminant) show smoother drops in the i-z and z-y colors, and are redder in y-J (>0.8).

From the PS1 data set, we have selected faint ($y > 19$), unresolved sources with no proper motion and colors consistent with being a quasar at high-z (i.e., a drop of > 2 mag corresponding to the observed Lyα wavelength and no detection in g and r). We have produced $1' \times 1'$, unconvolved weighted mean stacks of all the izy images of each of these sources and perform independent photometry. The candidates are then matched with the NIR/MIR information from VISTA, UKIDSS and WISE, and with NIR photometric observations obtained in a parallel program at the 2.2m telescope in La Silla (through MPIA granted time). This allows us to further clean the candidate sample. Simple colour cuts produced >20 candidate quasars per square degree. Our automated routines significantly reduces the number of candidates by carefully selecting only point sources, the removal of candidates in the halo of very bright stars and aperture photometry on the images. Cross-matching with SDSS and other wide–field surveys also allows to get rid of contaminants which are still bright in blue optical bands. Our routines successfully decrease the number of candidate quasars to 1 per $>$4 deg^2.

This program: Here we propose to collect spectra of a **suitable sample** ($\sim$ 50 **targets) of high-z quasar candidates** resulting from the PS1 data. This will allow us to confirm the high-z quasar nature of these objects and to measure their redshift. We followed this strategy in previous observations, which included a handful of candidates selected from the small portion of sky from which PS1 stacked catalogues were already available. **The stacked data catalogues have made the PS1 quasar search far more efficient, with eight new $z \sim 6$ quasars delivered by last year's MMT run alone.** In total, PS1 has now discovered 31 bright quasars at $z > 5.6$, more than from the SDSS.

This project aims to discover a sizeable sample of bright high-z quasars, which will constitute the ideal sample for follow-up investigations using, e.g., LBT, VLA and ALMA, aimed at characterizing the central black hole mass and accretion rate, the metallicity of the gas surrounding the singularity, the properties of the IGM on the line of sight, and the mass, star formation rate, and molecular gas content of the host galaxies.

Using the recently produced PS1 stacked catalogues, our aim is to discover a complete sample of z$\sim$6 quasars down to a z magnitude of 19.5-22.0, i.e. more than a magnitude deeper than the SDSS quasar search. Furthermore, based on the earlier detections of z>6.5 quasars in e.g. UKIDSS, we expect at least 2 very bright ($M_{\rm UV}$=-27) quasars at z>6.5 to be detectable by PS1. These quasars will be ideal for follow-up observations using VLA and ALMA. We propose to acquire low-resolution spectra of our PS1 quasar candidates, in order to measure their redshift.

REFERENCES: Bouwens & Illingworth 2006, Nature, 443, 189 • Bouwens et al. 2010, ApJ, 725, 1587 • Bouwens et al. 2011, Nature, 469, 504 • Bunker et al. 2004, MNRAS, 355, 374 • Castellano et al. 2010, A&A, 524, 28 • De Rosa et al. 2011, ApJ, 739, 56 • Fan et al. 2001, AJ, 122, 2833 • Fan et al. 2003, AJ, 126, 1649 • Fan et al. 2004, AJ, 128, 515 • Fan et al. 2006, AJ, 132, 117 • Haiman & Cen 2002, ApJ, 578, 702 • Kurk et al. 2007, ApJ 669, 21 • Labbé et al. 2010, ApJ Letters, 716, 103 • Labbé et al. 2012, (arXiv:1209.3037) • Morganson et al. 2012, AJ, 143, 142 • Mortlock et al. 2011, Nature, 474, 616 • Yan & Windhorst 2004, ApJ, 600, L1

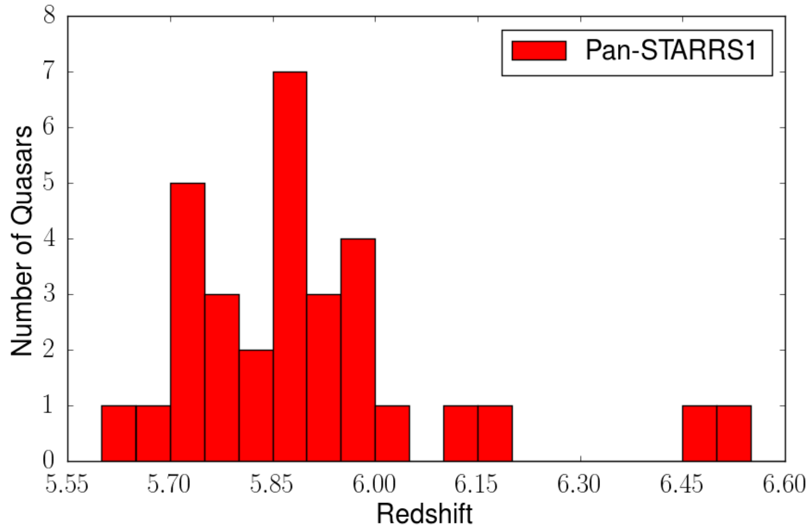

Figure 1: Redshift distribution of PS1 quasars. The discovery rate has increased dramatically due to improved reductions and stacking of multi-epoch data, and quasars at $z > 6$ are now being discovered using the deeper y-band data.

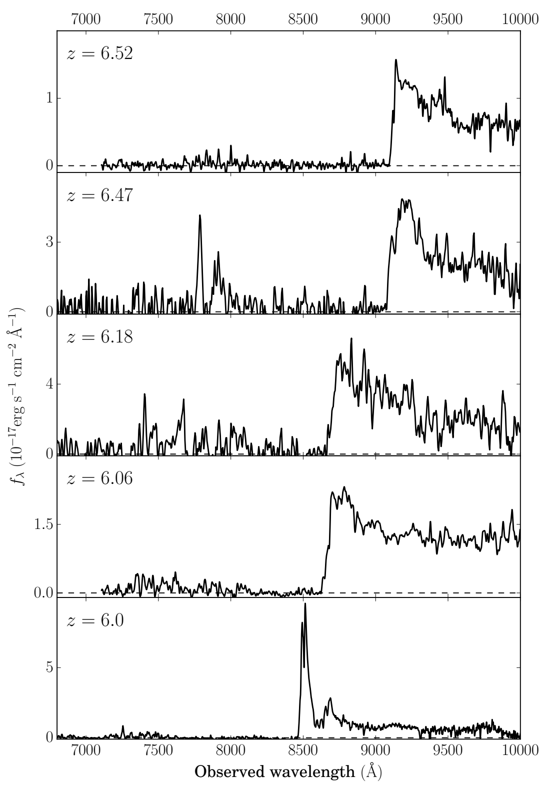

Figure 2: Newly discovered quasars up to $z = 6.5$ from Pan-STARRS. The new reductions allow quasars to be selected at much higher redshifts, providing bright quasars crucial for reionization-epoch studies at $z \sim 6.5$.

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)***

Our experience with Red Channel has shown that $z \sim 6$ quasars at this brightness can be identified in ~ 20–30 minute spectra. Although the candidates are relatively bright, they are very red and the sky noise due to the OH forest is severe, particularly for the $z \sim 7$ candidates. On the other hand, Red Channel has excellent red sensitivity ($\lambda > 9000$Å) and is well-suited for $z \sim 7$ quasars. We will use the low-res (270gpm) grating for maximal wavelength coverage. As we are working at red wavelengths gray time is suitable.

In 2011 we used Red Channel to confirm the first $z \sim 6$ quasar from Pan-STARRS, since then the photometry has improved considerably due to the availability of stacked images. We expect to have ~ 50 candidates remaining after the follow-up imaging, hence the request for three nights.

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 used two nights of MMT/SWIRC and two nights of MMT/Red in 2011 for the first investigation of PS1 candidates, leading to the first $z \sim 6$ quasar discovery from Pan-STARRS (Morganson et al. 2012). We also received two more nights in 2012 for the same program. This was still prior to the availability of stacked images and no new quasars were found. In 2013 we received three nights, and eight new z$\sim$6 quasars were discovered.

This work is in collaboration with a group at MPIA Heidelberg that has been leading a Pan-STARRS high-z quasar follow-up program. They have been using several nights of imaging follow-up time on Calar Alto and La Silla each semester. Our group at UofA has played a key role the spectroscopic follow-up; in particular, now that candidate selection has significantly improved, there are more good quasar candidates than the MPIA group has spectroscopic resources to cover.

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 quasar follow-up. One paper published, one ready to submit.
- ⋆ 2013B: three nights on MMT for PS1 quasar follow-up. Eight new PS1 quasars at z∼6. One paper published, one in preparation.
- Fall 2013, 15 nights on Bok for deep u-band imaging for SDSS-IV target selection.
- Spring 2013, Fall 2012, Spring 2012, six nights on LBT/LUCI for $z \sim 7$ galaxy spectroscopy. One paper published, one paper submitted.
- Fall 2013, Fall 2012, Spring 2012, Fall 2011, LBT/LUCI, ToO proposal for high-redshift GRBs, no triggers yet
- Spring 2012, 1 night blue channel, 1 night LBC, on surveys of massive protoclusters at $z \sim 2$. Blue channel and LBC observations successful. Some interesting systems discovered. LBT/MODS follow-up planned.
- Fall 2012, Spring 2011, 4 nights on MMT/SWIRC, 2 nights on MMT/Red, $z \sim 7$ quasar survey. The first $z \sim 6$ quasar from Panstarrs discovered from the data. One paper published, one paper ready to submit.