THE FIRST HIGH-REDSHIFT QUASAR FROM Pan-STARRS

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ABSTRACT

We present the discovery of the first high-redshift ($z > 5.7$) quasar from the Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1 or PS1). This quasar was initially detected as an $i_p$ dropout in PS1, confirmed photometrically with the SAO Wide-field InfraRed Camera at Arizona’s Multiple Mirror Telescope (MMT) and the Gamma-Ray Burst Optical/Near-Infrared Detector at the MPG 2.2 m telescope in La Silla. The quasar was verified spectroscopically with the MMT Spectrograph, Red Channel and the Cassegrain Twin Spectrograph at the Calar Alto 3.5 m telescope. Its near-infrared spectrum was taken at the Large Binocular Telescope Observatory (LBT) with the LBT Near-Infrared Spectroscopic Utility with Camera and Integral Field Unit for Extragalactic Research. It has a redshift of 5.73, an AB $z_p$ magnitude of 19.4, a luminosity of $3.8 \times 10^{47}$ erg s$^{-1}$, and a black hole mass of $6.9 \times 10^9 M_\odot$. It is a broad absorption line quasar with a prominent Ly$\beta$ peak and a very blue continuum spectrum. This quasar is the first result from the PS1 high-redshift quasar search that is projected to discover more than 100 $i_p$ dropout quasars and could potentially find more than 10 $z_p$ dropout ($z > 6.8$) quasars.

Key words: early Universe – quasars: individual (PSO J215.1512–16.0417) – surveys

1. INTRODUCTION

Quasars are massive black holes in the centers of galaxies that have large accretion rates and correspondingly large luminosities (Rees 1984; Antonucci 1993; Kembhavi & Narlikar 1999). They can be up to 100 times brighter than their host galaxies (e.g., Villata et al. 2006) and can thus be observed spectroscopically and analyzed in depth at higher redshifts than galaxies without quasars. High-redshift ($z > 5.7$) quasars are an essential tool for probing the early universe. Obtaining a statistically complete set of $z \approx 6$ quasars constrains early structure evolution and black hole formation (e.g., Jiang et al. 2008). Quasar spectra can be used to probe the evolution of metal abundances (Freudling et al. 2003; Jiang et al. 2007; Kurk et al. 2007, 2009; De Rosa et al. 2011). By observing the Gunn–Peterson troughs (Gunn & Peterson 1965) in the spectra, one can put constraints on the neutral hydrogen fraction ($H_\text{i}$) in the early universe (e.g., Becker et al. 2001; Fan et al. 2002; Fan 2006; Bolton et al. 2011) and directly probe the end of cosmic reionization.

Redshift $z \approx 6$ quasars’ usefulness as a probe of the early universe has led to significant interest and several extensive searches. Fan et al. (2001) first discovered them in the Sloan Digital Sky Survey (SDSS; York et al. 2000). Several searches in the last decade have found a total of roughly 60 quasars at $z \approx 6$ (Fan et al. 2006; Jiang et al. 2008; Willott et al. 2010). Extrapolating the statistics from Jiang et al. (2008) suggests that there are $\approx 450$ redshift $6 < z < 7$, AB magnitude $z < 21$ quasars in the entire sky.

Quasar searches have been slow to extend the redshift range of known quasars. Fan et al. (2001) included a $z = 6.28$ quasar and until 2011 subsequent searches only found quasars up to $z = 6.43$ (Fan et al. 2003; Willott et al. 2007). This is to be expected, as the main method of identifying $z \approx 6$ candidates is as “$i$ dropouts.” These sources are observable in the SDSS (or other surveys’) $z'$ filter, but are either not observable or very faint in the $i'$ band. At high redshift, this large $i' - z'$ color is due to the Ly$\alpha$ break at rest frame 1216 Å producing a Gunn–Peterson trough. The transition between the SDSS $i'$ and $z'$ band is at $\approx 8200$ Å, and the $z'$ band transmission drops markedly at wavelengths greater than 9000 Å (Fukugita et al. 1996). This limits the observation of quasars to the $z < 6.5$ redshift range in SDSS and surveys with similar filter sets.

The UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), made using the United Kingdom Infrared Telescope (UKIRT), is capable of finding quasars at higher redshift than SDSS and similar surveys. The UKIDSS Large Area Survey (LAS) will eventually cover 3800 degree$^2$ of SDSS area in $YJHK$ with average $Y$ depth is 20.2. Mortlock et al. (2008) have begun searching for quasars up to $z = 7.2$ as $z'$ dropouts, sources detected in $Y$ that are either faint or undetected in SDSS $z'$. UKIDSS’s area and depth will allow it to detect a handful of $z \approx 7$ quasars, and Mortlock et al. (2011) recently reported their first detection. UKIDSS also uses infrared color information to find new $z \approx 6$ quasars (Venemans et al. 2007).

In this paper, we discuss our $z \approx 6$ and $z \approx 7$ quasar search (Price et al. 2007) in the Panoramic Survey Telescope and Rapid Response System 1 (PS1; Kaiser et al. 2002). In the next section we discuss the PS1 data set and why it is ideal for searching for both $z \approx 6$ and $z \approx 7$ quasars. In Section 3, we explain how we currently select candidates and how this selection can become more efficient as the project matures. In Sections 4 and 5, we discuss the photometric and spectroscopic follow-up that is necessary to confirm our quasar candidates. We present the first PS1 $z \approx 6$ quasar in Section 6 and discuss its implications in Section 7.

2. THE PS1 DATA SET

PS1 (Kaiser et al. 2002, 2010; Chambers 2011) is a 1.8 m optical telescope with a 7 degree field of view that can image the
sky in the $g_{\pi P1}$, $r_{\pi P1}$, and $z_{\pi P1}$ filters which cover the 4000 Å < \( \lambda < 9200 \) Å spectral range similarly to the analogously named SDSS $g'$, $i'$, and $z'$ filters. It also has a $y_{\pi P1}$ filter which, including the spectral response of the camera, covers the 9200 Å < \( \lambda < 10500 \) Å range. The telescope is producing several surveys including a solar system Near Earth Object survey, a Stellar Transit Survey, a Deep Survey of M31, a Medium Deep Survey of our galaxy, and a 3σ survey, a Stellar Transit Survey, a Deep Survey of M31, a fainter quasars, analogous to the faint quasar search in SDSS (Richards et al. 2006). The PS1 Medium Deep survey will also allow us to search for fainter quasars, analogous to the faint quasar search in SDSS Stripe 82 in Jiang et al. (2008).

The PS1 3σ survey takes four exposures per year with each of the $g_{\pi P1}$, $r_{\pi P1}$, $i_{\pi P1}$, and $z_{\pi P1}$ filters. The yearly fill factor is roughly between 90% and 95% in each band. The missing area is due mostly to non-detection areas on the camera plane and weather restricting us to two or rarely zero exposures in some areas of the sky. Individual $g_{\pi P1}$, $r_{\pi P1}$, $i_{\pi P1}$, and $z_{\pi P1}$ exposures have median 3σ limiting AB magnitudes of 21.9, 21.8, 21.5, 20.7, and 19.7, respectively. These are median results of the last year of telescope performance, and recent hardware and software improvements have improved limiting magnitude by up to 0.3 mag. Stacked images are not yet available, and the work presented here is based on single exposure detections. However, when stacks are made, we expect a single year’s stacked image to increase each limiting magnitude by approximately 0.7 magnitude (accounting for some survey incompleteness), and the stacks of the proposed three year duration of the survey to increase them by 1.2. We see in Table 1 that in the $i_{\pi P1}$, $z_{\pi P1}$ bands, which are critical for detecting $z > 5.7$ quasars, PS1 will probe deeper than the SDSS. At 30000 deg² (minus approximately 40000 deg² since we do not search for quasars in the galactic plane), PS1 is also significantly larger than SDSS DR8 (140000 deg²) and the UKIDSS LAS (3800 deg²). Finally, the PS1 $z_{\pi P1}$ filter has a sharper red cutoff than the SDSS $z'$ filter. This should allow us to be particularly efficient at finding relatively low-$z$ $z_{\pi P1}$ dropouts.

This huge area and depth in the red bands will enable searches for many $z > 5.7$ quasars. Fan et al. (2006) found 19 $i'$ dropout quasars in 6600 deg². PS1 probes a half magnitude deeper in $i_{\pi P1}$ and covers nearly four times the searchable area. If we assume a quasar luminosity function of \( \Phi(L) \propto L^{-3} \) (Richards et al. 2006b), we expect to find \( \approx 200 \). Analogously, the PS1 area and $z_{\pi P1}$ depth will allow us to find several times as many quasars as the 3800 deg² UKIDSS LAS in which Venemans (2007) expects to find approximately 10 $z > 6.5$. PS1 does not have \( JHK \) bands that UKIDSS uses to select quasars, so it is difficult to estimate exactly how much more efficient the $z_{\pi P1}$ depth will make the PS1 search.

### 3. Candidate Selection

PS1 is a young survey and neither its catalogs nor its images exist in their final form. Our current method of selecting candidates will change as the data and image processing are improved. We will thus describe how we currently find candidates and how we plan to do so when the PS1 stacked imaging and catalogs have been produced.

Currently, we require sources be detected twice in their detection band ($y_{\pi P1}$ for $z_{\pi P1}$ dropouts and $i_{\pi P1}$ for $i_{\pi P1}$ dropouts). The 3σ survey takes either two or four exposures of every part of the sky in each band every year, so this requirement does not reduce our effective survey area significantly. We require that these two detections not be flagged as cosmic rays, saturated pixels, defects, blended sources or other suspicious entities. We also require that the sources be either 1.5 mag fainter or undetected in all bluer bands. In the future, we will raise this dropout requirement to 2 mag to exclude brown dwarfs and other contaminants, but in the first run we were interested in characterizing our false detections. We require that candidates be fainter than AB magnitude 18.5 in their detection band (the $z'$ magnitude of the brightest SDSS $i'$ dropout). This eliminates some extra spurious sources near bright galaxies and stars. For $i_{\pi P1}$ dropouts, we require that they be brighter than $z_{\pi P1} = 20.5$, since a huge number of faint $i_{\pi P1}$ dropouts will be undetected in bluer bands. We also require that objects be more than 10 degrees away from the galactic equator to avoid confusion by galactic stars and most galactic reddening.

When we performed this search, the PS1 database did not differentiate between sources that are covered by good imaging in a band but not detected in that band and sources that are not covered by good imaging (or any imaging). Approximately 10⁵ sources had detection in only the $y$ band, but the vast majority of apparent dropouts were simply not imaged in bluer bands. We eliminated false candidates by requiring that they be within the circular approximation of at least one exposure in every filter. We also require a dropout band detection (even a defect or cosmic ray) within 5σ of our source to ensure that there is data coverage in the immediate area of the detection. When the data is ultimately stacked, we will have a magnitude or limiting magnitude in every filter at every point and this step will be unnecessary. Finally, we eliminated candidates with “bright” neighbors (excluding defects and cosmic rays) within 2σ. Here, “bright” means that the neighbors were detected in bands bluer than the detection band and were not at least 0.5 mag dimmer than the candidate’s detection band magnitude. This last requirement eliminated sources whose blue detections were not matched to their red detections by the PS1 software. This left 10⁵ sources, a small enough number to process at the pixel level and analyze using the automated technique described below.

At the time of this writing, PS1 has just begun producing 3σ stacked images and corresponding catalogs which assign a limiting magnitude to sources that are not detected in a given filter and indicate which sources are only imaged in some bands. In addition, a second year of data is already filling in the areas which were not covered due to chip gaps and other holes in the imaging and catalogs have been produced.
our images. So the number of false positives at this stage is decreasing exponentially.

We obtain postage stamps of the 10^5 candidates which passed catalog level filtering from the Postage Stamp Server maintained by the PS1 Image Processing Pipeline team at the Institute for Astronomy. For each candidate, we obtain 24'' postage stamps of every exposure from the dropout band and detection band. We produce weighted mean stacks of these exposures and perform forced photometry on each stacked image. Approximately half of all candidates, at this stage, are eliminated because there are in small image gaps in the detection band. We also automatically eliminate all sources with more than 0.15 magnitude uncertainty in the stacked detection band image. This cut was judged, by eye, to be complete for real sources. We require that sources be 1.5 mag fainter in the dropout band than in the detection band if they are detected or have a 5σ limiting magnitude 1.5 mag greater than the detection magnitude. We also require that sources have 80% of their point-spread function flux imaged by good pixels to ensure that they are not chip edge or other artifacts. In cases where an object had been imaged in the detection band on two nights, we eliminated sources that were detected one night but not on another night of sufficient depth.

Finally, we examine the stacks and individual exposures of the remaining 3 \times 10^3 sources by eye. At this level, we eliminate cosmic rays and saturation defects that the software missed, marginal detections and artifacts registered as sources. There are approximately 10^3 candidates that passed visual inspection. We prioritize our follow-up candidates based on the reliability of the detection, the size of the color difference and observability from the observation site. So far, we have performed some follow-up on \approx 200 quasar candidates.

### 4. CANDIDATE FOLLOW-UP: PHOTOMETRY

Confirming a candidate requires more photometric information than PS1 can provide. In individual exposures, most $z > 5.7$ quasars will be near the PS1 detection limit, and it is difficult to reject asteroids which are detected in the detection band but have moved when that area is covered by other bands, so simply confirming the existence of a candidate is important. In addition, brown dwarfs and other red objects can have similar PS1 colors to high-redshift quasars (Fan 1999), so obtaining deeper $izy$ photometry for $i_P$ dropouts and $zyJ$ photometry for $z_P$ dropouts is essential to remove false candidates. We confirm our candidates with photometry from small telescopes before moving on to the more expensive spectroscopy necessary for deeper analysis.

Initially, we planned to confirm candidates using the Calar Alto 3.5 m telescope and the Omega 2000 camera with the $Y$ and $J$ filters in spring 2011. Unfortunately, the telescope was offline due to a mechanical failure for a period of many months that included our observation time. Fortunately, we also obtained five nights of time, 2011 February 16–20, with Multiple Mirror Telescope SAO Wide-field InfraRed Camera (MMT SWIRC). For each source, we took nine 30 s exposures in $Y$ band. This initial sample of sources was chosen to aggressively probe very faint sources, allowing for some false detections as a result of statistical noise. In addition, we did not account for moving solar system objects in our search. Only 23 of the 100 sources we followed up on were confirmed. This was to some degree expected, as coincident noise peaks and slow-moving objects which can be detected twice on one night are both plentiful in our large data set. This work helped us understand how to select sources efficiently near our limiting magnitude.

We used GROND, a $grizJHK$ simultaneous imager at the 2.2 m telescope in La Silla, to obtain colors of the confirmed candidates from our MMT run and 39 additional candidates (Greiner et al. 2008). The observations occupied roughly 40% of a 10 night observation period, 2011 March 4–13. Each object was observed using an instrument standard “8 minute observation block” in which the infrared images get a total of 8 minute exposure time and the optical bands get slightly less. We detected 48 of 62 sources, but found that most of them were less red than they had appeared in PS1. This was expected, since our typical PS1 colors have uncertainties of a few tenths, and we find many common bluer objects which had randomly scattered to pass our $i_P - z_P$ or $z_P - y_J$ cut. We did find one very promising candidate (finding chart in Figure 1 and multi-filter imaging in Figure 2), PSO J215.1512−16.0417 (at J2000 215.1512, −16.0417 or 14h20m36.3, −16°02′30.2, −16°02′09.1).

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We reduced the image data using IRAF\textsuperscript{6} routines. Images were processed with pipelines developed for this purpose by

\textsuperscript{6} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
our group. Individual frames were bias and dark subtracted and flat-fielded. Median sky images, created by stacking individual exposures without realignment, were scaled to the median counts in each frame and subtracted. Images were then realigned and combined. The astrometric solution was computed using the Astrometry.net software (Lang et al. 2010). Photometric zero points were computed by comparing instrumental magnitudes of field stars with the values reported in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and PS1 databases. The resulting photometric uncertainties were \( \sim 0.05 \) mag, and systematic uncertainties due to differences in filters were \( \sim 0.1 \) mag.

5. CANDIDATE FOLLOW-UP: SPECTROSCOPY

We had spectroscopic follow-up time with both the MMT Red Channel Spectrograph (2011 March 12–13) and the Calar Alto TWINS (2011 April 9–12). We used a 1'' slit at MMT and a 1.5'' slit at Calar Alto. We examined PSO J215.1512−16.0417 and 13 others which had a less dramatic dropout color and were thus less likely to be quasars. The majority of these candidates were \( i_{\text{PS1}} \) dropouts which we had not examined with GROND. We confirmed that our most likely candidate was indeed a quasar (as we discuss in Section 6). We tentatively identified the other candidates as M, L, and T dwarfs as well as three galaxies with particularly bright emission lines in our observation band, and have performed no additional follow-up on them.

Finally, we used the LBT NIR Spectroscopic Utility with Camera and Integral-Field Unit for Extragalactic Research (LUCI) at the Large Binocular Telescope (LBT) to measure the near IR spectrum of our quasar and estimate the continuum power law on 2011 May 28. We used a 1'' slit.

Optical spectroscopic data were reduced using standard IRAF tools. After bias subtraction and flat-field correction, we aligned exposures by matching the position on the slit of bright field sources. Frames were combined using the \texttt{crreject} algorithm to get rid of cosmic rays. Wavelength calibration was achieved through the acquisition of He/Ar arc spectra, and compared with the observed sky emission lines (mainly OH) to correct for instrument flexure. Typical uncertainties in the wavelength calibration are \( \sim 0.2 \) Å over the observed range. Spectra of spectrophotometric standard stars were collected, in order to perform relative flux calibration.

LUCI observations were collected using the standard nodding technique for NIR spectroscopy. Data were reduced using our own IRAF-based pipeline. Differences between frames in A and B position were computed in order to achieve optimal sky subtraction. We aligned and stacked the A–B and B–A frames independently, applied wavelength calibration then extracted and combined the resulting one-dimensional spectra. Dispersion solution is computed from the OH lines observed on the target spectra. Correction for telluric absorption and flux calibration were achieved by comparing the spectrum of the telluric standard Hip71451 with the model of the model spectrum of a B9 star. Absolute flux calibration for both optical and NIR spectra was performed by scaling them to match the GROND photometry in \( z \) or \( J \). GROND was in turn calibrated to 2MASS.

6. THE FIRST PS1 HIGH-REDSHIFT QUASAR

PSO J215.1512−16.0417, the candidate we identified as our most likely quasar (and not coincidentally the first candidate we observed spectroscopically), was confirmed as a quasar at MMT and Calar Alto. We present the spectrum from each

\[ \text{http://www.eso.org/sci/facilities/paranal/instruments/isaac/tools/lib/index.html} \]
observatory and the PS1 filter curves in Figure 3. Comparing the spectra to the filter curves, we see that if this object were at significantly lower redshift, it would have had significant $i_{P1}$ flux and would not have been detected as an $i_{P1}$ dropout. In Figure 4 we include the LBT NIR spectrum and compare it to the GROND photometry.

We analyze this quasar in Figures 5 and 6. We use the long infrared/optical baseline that our MMT and LBT spectra provide in Figure 5 to find that our continuum is well fit by a $\lambda^{-3.05}$ power law, much bluer than the SDSS $z \approx 4$ average of $-1.3$ (Vanden Berk et al. 2001). This estimate was made using the continuum region around 1420 Å from the MMT spectrum and the entire LBT spectrum following De Rosa et al. (2011). The exponent has statistical error of 0.05.

Having modeled the continuum, we fit the Ly$\alpha$, N$\nu$, Si$\nu$, O$\iota$, and C$\nu$ lines as Gaussians, masking high absorption regions where appropriate. We fit Ly$\alpha$, N$\nu$, Si$\nu$ simultaneously because they are less than an FWHM. But the other peaks are fitted independently. See Table 3 for details. We do not fit the Si$\nu$-O$\nu$ complex at 1400 Å because of broad absorption features. The Ly$\alpha$ peak is only a marginal detection and is several Å from its expected location. This and a small Si$\nu$ absorption at observer 9250 Å (see Figure 3) leads us to believe that this quasar is a broad absorption line (BAL) quasar. We thus refit the Ly$\alpha$-N$\nu$-Si$\nu$, fixing the Ly$\alpha$ peak wavelength using the O$\iota$ redshift. We present both the “free” (non-BAL) and “fixed” (BAL) results. For the remainder of this paper, we use values consistent with the BAL assumption.

We estimate the redshift to be $5.7321 \pm 0.0065$ using the O$\iota$ line in Figure 6, which is our most statistically robust emission line. Using the “fixed” fit, the lines have a measured redshift scatter of 0.02 (see Table 3), which represents the astrophysical systematic uncertainty. If we refit our peaks with the (SDSS average) $\lambda^{-1.3}$ power-law continuum, the redshifts only shift by 0.004, so our dominant source of uncertainty appears to be astrophysical. Our final redshift estimate is $5.73 \pm 0.02$.

We have no Mg$\nu$ or C$\nu$ line in our spectrum and cannot measure our quasar’s black hole mass and bolometric luminosity in the most precise way. Instead, we measure the flux at 1350 Å is $1.89 \times 10^{-16}$ erg Å$^{-1}$ cm$^{-2}$ s$^{-1}$. Multiplying by $4\pi D^2$ yields a monochromatic luminosity of $9.5 \times 10^{46}$ erg s$^{-1}$. We multiply this by the bolometric coefficient of 3.81 from Richards et al. (2006a), to obtain a bolometric luminosity of $3.8 \times 10^{47}$ erg s$^{-1}$ with 0.2 dex of uncertainty. This in turn corresponds to an Eddington Mass of $2.9 \times 10^9 M_\odot$. In an analysis of the complete set of SDSS high-redshift quasars, De Rosa et al. (2011) find that bright ($L > 10^{47}$ erg s$^{-1}$) $z \approx 6$ quasars have typical Eddington
Figure 6. Rest-frame MMT spectrum of PSO J215.1512−16.0417 fitted with pertinent emission lines (excluding Lyβ) and continuum. We present the BAL model in which the Lyα wavelength is fixed (gray) and the model in which the Lyα wavelength is free (black).

Table 3

| Line      | \(\lambda_{\text{peak}}\) (Å) | \(z\)      | Flux \((10^{-15}\text{ erg cm}^{-2}\text{ s}^{-1})\) | FWHM (Å) | EW (Å) |
|-----------|-------------------------------|------------|---------------------------------|----------|--------|
| Lyα (free)   | 1231 ± 18                     | 5.810 ± 0.098 | 15 ± 12                         | 33 ± 20  | 107 ± 83 |
| N\(\text{v}\) (free) | 1244.97 ± 0.89               | 5.7465 ± 0.0048 | 0.38 ± 0.43                     | 6.5 ± 0.40 | 2.5 ± 2.9 |
| Si\(\text{ii}\) (free) | 1268.49 ± 0.97                | 5.7554 ± 0.0051 | 1.26 ± 0.32                     | 13.1 ± 2.0 | 8.0 ± 2.0 |
| Lyα (fixed)  | 1215.67                       | 5.7321      | 38 ± 17                         | 44.4 ± 5.5 | 280 ± 130 |
| N\(\text{v}\) (fixed) | 1245.36 ± 0.39               | 5.7567 ± 0.0022 | 0.23 ± 0.15                     | 2.9 ± 1.4  | 1.5 ± 1.0 |
| Si\(\text{ii}\) (fixed) | 1267.21 ± 0.59               | 5.7567 ± 0.0032 | 1.14 ± 0.20                     | 12.7 ± 1.6  | 7.3 ± 1.3 |
| O\(\text{i}\)     | 1306.9 ± 1.3                  | 5.7321 ± 0.0065 | 1.24 ± 0.25                     | 22.1 ± 3.7  | 7.4 ± 1.4 |
| C\(\text{ii}\)    | 1339.50 ± 0.72               | 5.7452 ± 0.0036 | 0.43 ± 0.11                     | 9.4 ± 2.1   | 2.35 ± 0.64 |

Notes. All error bars are statistical. We include the fitted central wavelength, integrated flux, line width, FWHM, and equivalent width. Because of the (likely) broad absorption feature, we fit the Lyα-N\(\text{v}\)-Si\(\text{ii}\) complex with the position of Lyα peak free and separately fit the Lyα with a peak with its position fixed by the O\(\text{i}\) redshift measurement.

ratios of 0.43 with 0.2 dex dispersion. We thus estimate our black hole mass to be \(6.9 \times 10^9 M_\odot\) with 0.3 dex uncertainty. Our quasar’s blue continuum suggests that its bolometric luminosity may be even higher than this “typical quasar” analysis suggests, but it is difficult to model this effect reliably.

When we compare PSO J215.1512−16.0417 to other \(z \approx 6\) quasars (Figure 7), we see that it has at least three interesting features. First, it appears to be a BAL quasar which Trump et al. (2006) finds is true of only 10% of all quasars. In addition, PSO J215.1512−16.0417 has a very bright Lyβ peak that will allow us to more precisely study the hydrogen absorption along the line of sight in the future. PSO J215.1512−16.0417 is also one of the bluest known at this redshift. A more complete analysis and comparison of quasars will be described in De Rosa et al. (2011).

7. DISCUSSION AND CONCLUSIONS

PSO J215.1512−16.0417 is a very blue, (likely) BAL quasar with a prominent Lyβ peak that demonstrates the ability of PS1 to find \(z \approx 6\) quasars. We expect to find 100s of \(i_p\) dropouts that will allow us to make a statistically precise measurement of the \(z \approx 6\) universe. The survey also offers the exciting prospect of extending our measurements of Gunn–Peterson troughs, emission and absorption lines, and black holes masses to the \(z = 7\) regime.

Continued development of PS1 survey, hardware and software as well as our experience regarding follow-up observations will greatly increase our efficiency. At the time of our initial candidate selection, the \(i_p\) and \(z_p\) overlap regions were only a few thousand square degrees. In addition, several improvements to the PS1 telescope have decreased its background levels and FWHMs, increasing the limiting magnitude significantly. As PS1 finishes its second year, the data processing software has been (tentatively) finalized and many false positives in the database have been eliminated. This will allow us to examine more candidates. In addition, PS1 has recently begun producing stacked data which should immediately add roughly on magnitude depth and allow us to discriminate between sources which were not imaged in a band and sources which were imaged but too faint to be detected. Finally, our follow-up observations have emphasized the necessity of obtaining deep \(i_p\) observations for \(i_p\) dropouts and deep \(z_p\) observations for \(z_p\) dropouts.

PSO J215.1512−16.0417 is our first glimpse into a bright future \(z > 5.7\) discovery with PS1. With this survey we expect...
Figure 7. Comparison of PSO J215.1512−16.0417 to SDSS $z \approx 6$ quasars. PSO J215.1512−16.0417 has a prominent Lyβ feature. The sharp drop-off near the Lyα feature is probably due to a BAL. One can also see that this quasar is very blue and already dropping off significantly at 10000 Å.

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