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The discovery of eight $z \sim 6$ quasars from Pan-STARRS1

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Abstract. High-redshift quasars are unique probes of the evolution of supermassive black holes and the intergalactic medium at the end of the epoch of reionization. We present the optical spectra of eight new $z \sim 6$ quasars selected from the Panoramic Survey Telescope & Rapid Response System 1 (Pan-STARRS1). Details of the selection strategy can be found in Bañados *et al.* (2014). With this work we increase the number of known quasars at $z > 5.7$ by more than 10%. The quasars discovered here span a large range of luminosities ($19.6 \leqslant z_{\rm P1} \leqslant 21.2$) and are remarkably heterogeneous in their spectral features: half of them show bright emission lines whereas the other half show weak or no Lyα emission line. We find a larger fraction of weak–line emission quasars than in lower redshift studies, although still based on low number statistics, this may imply that the quasar population could be more diverse than previously thought.

Keywords. cosmology: observations, quasars: general, surveys: Pan-STARRS1.

1. Introduction

High-redshift quasars provide us with unique information about the evolution of supermassive black holes (SMBHs) and the intergalactic medium (IGM) at early cosmic time. For more than a decade, several groups have searched for quasars at $z > 5.7$, establishing a sample of ∼60 quasars (e.g., Fan *et al.* 2006b, Willott *et al.* 2009). These quasars have played an important role in studies of the formation and evolution of SMBH and the IGM at the end of the epoch of reionization (e.g., Fan *et al.* 2006a, Simcoe *et al.* 2012, De Rosa *et al.* 2013). These studies show that important changes are occurring in the IGM at $z \sim 6-7$. Therefore, the discovery and characterization of a statistically significant sample of bright quasars in this redshift range is crucial to further study this important era in the history of the Universe.

2. Pan-STARRS1 3π Survey

The Panoramic Survey Telescope & Rapid Response System 1 (Pan-STARRS1; Kaiser *et al.* 2010) consists of a 1.8-meter telescope located in Mount Haleakala on Maui, equipped with a 1.4 gigapixels camera. Pan-STARRS1 is surveying the whole sky north of declination $-30°$ in the filters $g_{\rm P1}$, $r_{\rm P1}$, $i_{\rm P1}$, $z_{\rm P1}$, and $y_{\rm P1}$. Every region of the survey is approximately imaged four times per year per filter.

Pan-STARRS1 represents a fundamental step forward in high-redshift quasar searches for three reasons: 1) it covers two times the area observed with SDSS; 2) it goes significantly deeper (0.5 - 1 mag) than SDSS in the reddest bands where $z \sim 6$ quasars are detected; and 3) the $y_{\rm P1}$-band facilitates the search of $z \sim 6$ quasars and enables the search for luminous quasars beyond the SDSS limit, $z > 6.5$.

Already in Morganson *et al.* (2012) we discovered the first $z \sim 6$ quasar selected from Pan-STARRS1. Our aim is to discover a complete sample of $z \sim 6$ quasars in the 3π Pan-STARRS1 area, sensitive to a magnitude of $z = 21.4$, i.e. nearly a magnitude deeper than the SDSS main quasar search.

3. Quasar Candidates Selection

Quasars at redshift $z \gtrsim 5.7$ are observationally characterized by their very red $i - z$ color and blue continuum (i.e., blue $z - y$ color). They are very faint or completely undetected in the i band due to the optically thick Lyα forest at these redshifts, causing that most of the light coming from wavelengths $\lambda_{\rm rest} < 1216$ Å to be absorbed.

Because high-redshift quasars are very rare and because of the high number of other sources (or artifacts) that mimic high-redshift quasar colors, we cleaned our sample in several steps which are explained in detail in Bañados *et al.* (2014). Here we briefly outline the most important steps:

(*a*) We selected initial high-redshift quasar candidates from the Pan-STARRS1 stacked catalog. In this work, we focused on the upper-left region of the color-color diagram in Figure 1.

(*b*) At the position of each candidate, we applied forced aperture photometry in the stacked images in order to corroborate the catalog colors.

(*c*) This was followed by forced photometry in all single-epoch $z_{\rm P1}$–band images to remove artifacts.

(*d*) We then matched the candidate list to the Two Micron All Sky Survey and performed forced photometry in the SDSS and UKIDSS images to eliminate contaminants that are evident when using the extra information provided by these surveys.

(*e*) We then cross-matched the remaining candidates with known quasars and visually inspected the stacked and single-epoch stamps to ensure that they are real.

(*f*) We then obtained optical and near-infrared follow-up photometry.

(*g*) Finally, we obtained spectra to confirm the nature and redshifts of the remaining candidates.

4. Results

In less than a year we have discovered eight new quasars at $z \sim 6$, whose spectra are shown in Figure 2. With this work, Pan-STARRS1 has now discovered a total of nine

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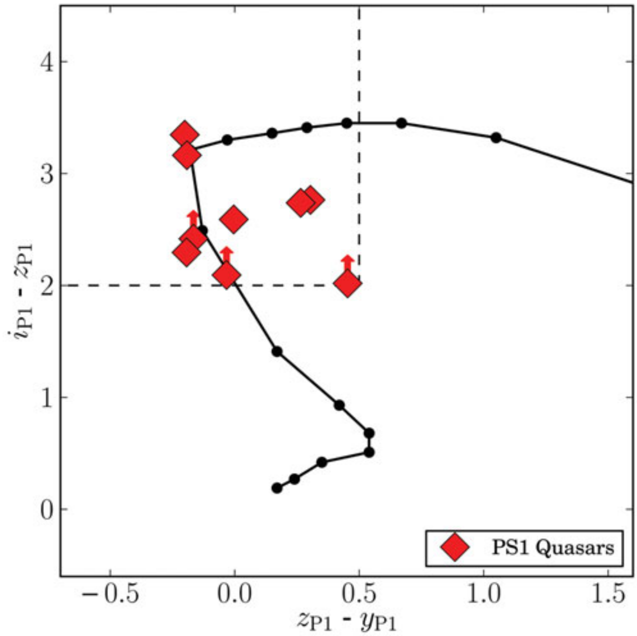

Figure 1. Color-color diagram showing the criteria used to select quasar candidates (dashed line, upper left corner). The thick line shows the expected color of the quasar template from Decarli *et al.* (2010) redshifted from $z = 5.0$ to $z = 6.5$ in steps of $\Delta z = 0.1$. The diamonds are the colors of the Pan-STARRS1 Quasars presented in Figure 2.

quasars at $5.7 \leqslant z \leqslant 6.0$, increasing the number of published $z > 5.7$ quasars by more than 10%. Follow-up observations are still on-going and the discovery of more quasars is expected, therefore conclusions on the luminosity function and the space density of $z \sim 6$ quasars are not possible at this time. The variety of spectral features among these quasars is remarkable, including four quasars with very bright emission lines and other four quasars with almost no detectable emission lines (see Figure 2). The fraction of weak-line emission quasars found in this work (25%) is much larger than fractions found by other studies at lower redshifts (4% – 6%, e.g., Diamond-Stanic *et al.* 2009) but consistent with the fraction in the SDSS main $z \sim 6$ quasar sample (Fan *et al.* in prep). Our new discoveries demonstrate that weak-line emission quasars could be more common than previous lower redshift studies indicated. For details and a more thorough discussion, please refer to Bañados *et al.* (2014).

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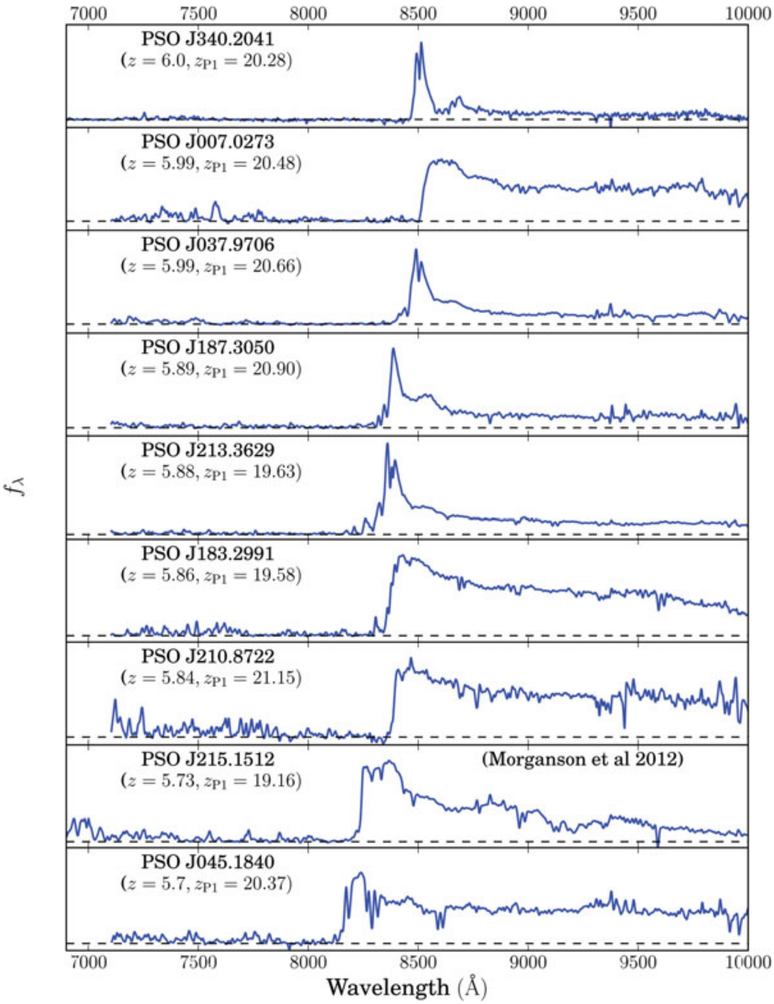

Figure 2. Spectra of the nine newly discovered Pan-STARRS1 quasars at $5.70 \leqslant z \leqslant 6.00$.

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