*AGN Physics with the Sloan Digital Sky Survey*
*ASP Conference Series, Vol. **VOLUME***, 2004*
*G.T. Richards and P.B. Hall, eds.*

# Counts of Low-redshift SDSS Quasar Candidates

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**Abstract.** We analyze the counts of low-redshift quasar candidates selected using nine-epoch SDSS imaging data. The co-added catalogs are more than 1 mag deeper than single-epoch SDSS data, and allow the selection of low-redshift quasar candidates using UV-excess and also variability techniques. The counts of selected candidates are robustly determined down to $g$=21.5. This is about 2 magnitudes deeper than the position of a change in the slope of the counts reported by Boyle et al. (1990, 2000) for a sample selected by UV-excess, and questioned by Hawkins & Veron (1995), who utilized a variability-selected sample. Using SDSS data, we confirm a change in the slope of the counts for both UV-excess and variability selected samples, providing strong support for the Boyle et al. results.

## 1. A Controversy About Quasar Counts

The quasar luminosity function, $\Phi(L)$, provides fundamental information about their nature. Boyle et al. (1990, 2000) found that $\Phi(L)$ for quasars at redshifts $z < 2.3$ resembles a "broken" power law which becomes *flatter* at the faint end. They also demonstrated that the "break" luminosity at which the slope changes increases with redshift, and between $z = 0.8$ and $z = 2.2$ becomes more luminous by 1.9 mag. A peculiar aspect of this result is that the apparent magnitude corresponding to the "break" luminosity changes by only 0.8 mag. over this redshift range ($B$=18.6–19.4; that is, the differential distribution of quasar apparent magnitudes has a shape very similar to the shape of their luminosity function). Further, this apparent magnitude range is only $\sim$ 1-2 mag. above the photographic plate limit used for selection. Therefore, it is possible that the flattening of the luminosity function is due to a systematic underestimate of the increasing incompleteness at the faint end of the UV-excess selection technique employed

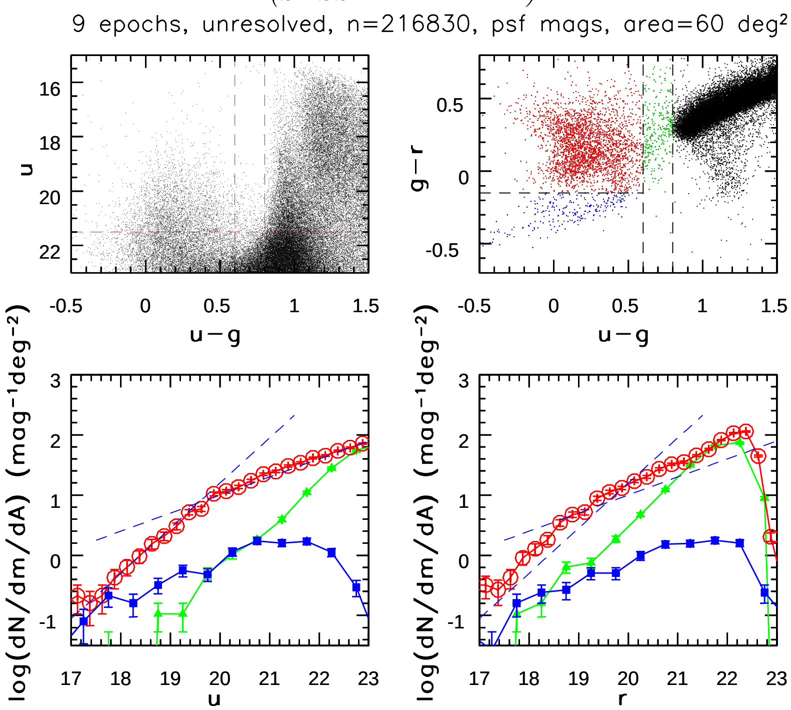


Figure 1. The top panels show the distribution of ∼220,000 point sources from 60 deg$^2$ of sky with 9 SDSS imaging observations in representative SDSS color-magnitude and color-color diagrams. The bottom two panels show differential counts for sources from three regions in the $g - r$ vs. $u - g$ color-color diagram: quasar candidates (circles, $u - g < 0.6$, $-0.15 < g - r < 0.8$), hot stars (triangles, $u - g < 0.6$, $< g - r < -0.15$), and quasar-star transition region (squares, $0.6 < u - g < 0.8$). The dashed lines, with slopes of 0.75 and 0.30, are added to guide the eye (same lines in both panels).

by Boyle et al. Indeed, Hawkins & Veron (1995), using a variability-selected sample with 300 objects, argued that "The luminosity functions for redshifts of less than 2.2 show a featureless power law, with no sign of a 'break'."

## 2. Can SDSS Resolve the Controversy?

The $z < 3$ SDSS (York et al. 2000) spectroscopic quasar sample is limited to $i < 19.1$, and thus not deep enough to reliably constrain the faint end of the luminosity function. The color selection by UV excess from the SDSS photometric sample (essentially based on SDSS $u - g$ color, see Richards et al. 2002 and references therein) is limited by the photometric accuracy in the $u$ band to $u \sim 21$, which would be just barely sufficient to detect a change of the slope of counts at $i \sim 20$. However, the coadding of SDSS multi-epoch photometry produces >1 mag. deeper $u$-band measurements at a given accuracy, and allows a robust identification of UV-excess selected candidates to $u \sim 22$. Furthermore, multi-epoch data can also be used to select quasar candidates by variability, using techniques similar to those employed by Hawkins & Veron. This is the first time that it is possible to contrast the conflicting results of Boyle et al. and Hawkins & Veron using the same homogeneous data set.

## 3. Color Selection

We selected low-redshift quasar candidates by requiring $u-g < 0.6$ and $-0.15 < g-r < 0.7$ (based on the criteria of Richards et al. 2002). Their counts, and counts for two control samples, are shown in Fig. 1. The differential counts of selected candidates rise steeply ($\log(N)$ vs. $m$ slope $\sim$0.75) at the bright end ($u < 19.5$, or $r < 19$), and then the slope changes to $\sim$0.30. This behavior is in agreement with the results of Boyle et al., who used a similar selection technique. It is worth emphasizing that SDSS photometric catalogs based on digital data are much more accurate (0.02 mag. errors, see Ivezić et al. 2003) than the catalogs used by Boyle et al. which were derived from a photographic survey. In particular, the gap between the distribution of quasars and more numerous blue thick disk and halo stars (centered on $u-g \sim 0.7$, see the top left panel in Fig. 1) cleanly separates the two populations.

We note that some of the UV-excess selected candidates are not quasars: the results of SDSS spectroscopic follow-up ($i < 19$) indicate that $\sim$ 20% are stars (dominated by white dwarfs). This correction, however, has no effect on the conclusion that the slope of differential counts changes because there are about 10 times fewer quasar candidates at $r \sim 21.5$ than predicted by extrapolating the counts for $r < 19$. Similarly, star/galaxy separation is not an issue: even if resolved sources were added to the point sources, the counts would be qualitatively unchanged (i.e. the UV-excess sources are heavily dominated by point sources).

## 4. Variability Selection

Quasars are variable sources with amplitudes of several tenths of a magnitude for time scales longer than a few months (e.g. Hawkins & Veron 1995). The top left panel in Fig. 2 shows the correlation between variability in the $g$ band, $|\Delta g|$, and $u-g$ color for point sources observed twice two years apart. A large majority of variable sources, defined by $|\Delta g| > 0.15$, show UV excess (84% for $u < 21.5$). Even without accounting for the fact that some variable sources are stars (which would further increase this fraction), this high fraction implies that UV-excess and variability selection techniques yield similar samples (see the two bottom panels in Fig. 2). Alternatively, 47% of sources selected by UV-excess have $|\Delta g| > 0.15$. It is therefore not surprising that the counts of variability-selected quasar candidates, which we define as *all* sources with $\Delta(g) > 0.15$, also show a change of slope at $r \sim 19$. Of course, this selection could be further refined; for example, RR Lyrae stars, which dominate the variable star population, can be easily removed due to their distinctive colors and much shorter variability time scale (Ivezić et al. 2000). Such improvements would only further increase the similarity of differential counts for UV-excess and variability selected quasar candidates.

## 5. Discussion

The counts of quasar candidates selected by both UV-excess and variability techniques using multi-epoch SDSS imaging data change slope around $r = 19$. This result provides strong support for the quasar luminosity function and its evolution advocated by Boyle et al., and demonstrates that both techniques produce similar samples when applied to high-quality data.

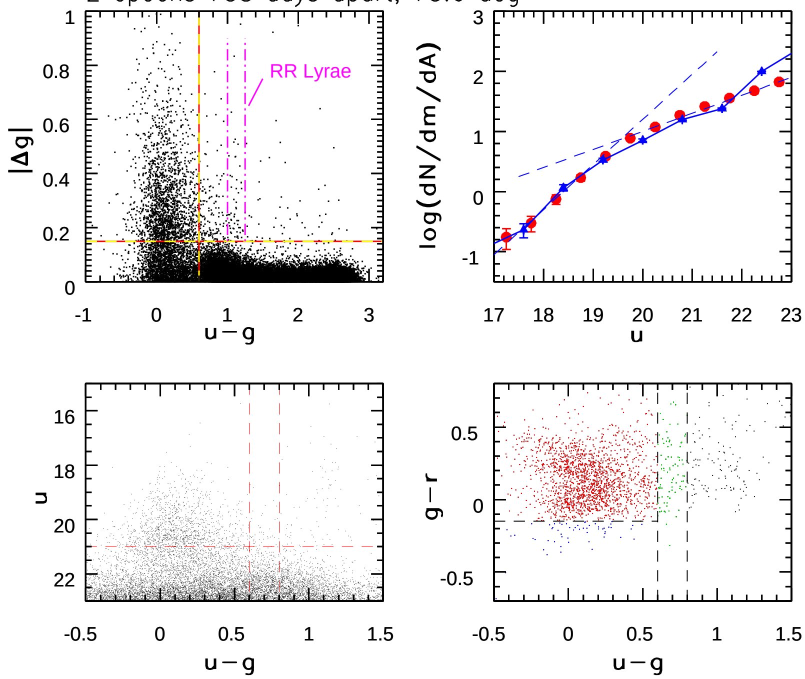


Figure 2. The top left panel shows the difference in $g$ magnitude as a function of $u-g$ color for 47,116 points sources with mean $u < 21.5$ observed twice $\sim$ 2 years apart. The vertical full line illustrates the UV-excess selection of low-redshift quasar candidates from Figure 1 ($u-g < 0.6$), and the horizontal line shows the adopted limit for the selection of variable sources ($|\Delta g| > 0.15$ mag). 84% of variable sources show UV-excess, and 47% of UV-excess selected sources have $|\Delta g| > 0.15$ mag. The top right panel compares the counts of sources selected by UV-excess (circles, same as bottom left panel in Fig. 1), and those selected by variability (triangles, renormalized at the bright end, $u = 19$). The dashed lines are the same as those in bottom left panel in Fig. 1. The bottom two panels show the distribution of variability-selected sources in color-magnitude and color-color (only $u < 21.5$) diagrams (compare to the top panels in Fig. 1).

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/.

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