HIGHLY VARIABLE OBJECTS IN THE PALOMAR-QUEST SURVEY: A BLAZAR SEARCH USING OPTICAL VARIABILITY

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ABSTRACT

We identify 3113 highly variable objects in 7200 deg^2 of the Palomar-QUEST (PQ) Survey, which each varied by more than 0.4 mag simultaneously in two broadband optical filters on timescales from hours to roughly 3.5 years. The primary goal of the selection is to find blazars by their well-known violent optical variability. Because most known blazars have been found in radio and/or X-ray wavelengths, a sample discovered through optical variability may have very different selection effects, elucidating the range of behavior possible in these systems. A set of blazars selected in this unusual manner will improve our understanding of the physics behind this extremely variable and diverse class of active galactic nucleus (AGN). The object positions, variability statistics, and color information are available using the PQ CasJobs server. The time domain is just beginning to be explored over large sky areas; we do not know exactly what a violently variable sample will hold. About 20% of the sample has been classified in the literature; over 70% of those objects are known or likely AGNs. The remainder largely consists of a variety of variable stars, including a number of RR Lyrae and cataclysmic variables.

Key words: BL Lacertae objects: general – catalogs – galaxies: active – quasars: general

1. INTRODUCTION

Palomar-QUEST (PQ) is one of the first surveys with repeated observations over a large fraction of the sky, and has the potential to find many rare variables. We have carried out a search for highly variable objects; while it is interesting to see the make-up of such a variability-selected list, the search is motivated by the desire to find blazars. A large optically identified set of blazars with selection effects different from current samples will help us to understand the range of blazar behavior and its underlying mechanisms.

Blazars are active galactic nuclei (AGNs) that emit jets and are aligned such that the jet axis is within about 15° of the line of sight. The jets are made up of highly energetic photons, electrons, positrons, and perhaps also hadrons which emit synchrotron radiation. This emission, or thermal emission from ambient particles, is Compton upscattered by the jet particles. The resulting spectral energy distribution (SED) exhibits two large bumps: a synchrotron peak typically centered in the radio and infrared range, and a higher energy peak spanning X-ray or gamma-ray wavelengths. The jet and its surroundings are inhomogeneous, the flux emanating from the shocks depends on the density of the matter involved, and the emission is highly beamed in our direction; the blazar flux is therefore extremely variable in time (see, e.g., measurements by Heidt & Wagner 1996; Ciprini et al. 2003; Kartaltepe & Balonek 2007).

Blazars are divided into two classes according to their optical spectral properties, in particular by how strongly the jet continuum dominates over flux from the accretion disk and emission line regions. BL Lacs have spectra that are featureless, where no emission lines show through the radiation from the jet. Flat spectrum radio quasars (FSRQs) instead show visible broad optical emission lines.

The central frequencies of blazars' two SED peaks appear to be correlated. The frequencies of the peaks depend on the highest energy of the electrons in the jet or the strength of the jet's magnetic fields, depending on the jet's emission mechanism (Fossati et al. 1998). The more energetic the jet particles or strong the magnetic field, the higher the frequencies. It is not clear, however, how these parameters relate to other properties of the blazar. BL Lacs are divided into two categories according to their peak frequencies: high peaked BL Lacs (HBLs) have synchrotron peak frequencies in the UV to soft X-ray bands, while low peaked BL Lacs (LBLs) have the synchrotron peak in the radio and IR. The HBL/LBL dichotomy was originally used to describe BL Lacs only, although FSRQs can be discussed in these terms as well. Most FSRQs have SEDs similar to LBLs, although some have SEDs more like HBLs (Padovani et al. 2007). HBLs and LBLs show differences beyond their SED peak frequencies. For example, LBLs are usually more luminous than HBLs, and in LBLs the high-frequency Compton peak dominates while in HBLs the low-frequency synchrotron peak tends to dominate.

Currently known blazars have almost entirely been found either by their bright radio or X-ray emission, or a combination of both. HBLs have traditionally been found using X-ray data, LBLs using radio data. Selection effects may significantly influence the types of blazars discovered to date. A sample of optically selected blazars may include many with atypical peak frequencies, perhaps in the continuum between the LBL and HBL blazars. Transitional objects with some features of both quasars and blazars may also be found (e.g., 3C 273; see Kataoka et al. 2002; Perlman et al. 2008). Collinge et al. (2005) and Londish et al. (2007) have selected candidate BL Lacs by looking for featureless optical spectra among color-selected quasar candidates in the Sloan Digital Sky Survey (SDSS) and

the Two-Degree Field (2dF) and Six-Degree Field (6dF) surveys, respectively. The samples need further follow-up to be securely identified; however, they appear to have roughly similar SEDs to known blazars (particularly HBLs), although they are perhaps less radio loud. A set of optical variability-selected blazars, with selection biases different from the current samples, would place important constraints on the nature of the different blazar types.

2. THE PALOMAR-QUEST SURVEY

The PQ Survey has observed 15,000 deg^2 of sky repeatedly using seven optical filters. It is a multipurpose project and is currently being used to study type I quasars (Bauer et al. 2009a), blazars (Bauer et al. 2009b), type Ia supernovae (Wood-Vasey et al. 2004), transients in real-time (Djorgovski et al. 2008), brown dwarfs (Slesnick et al. 2006a; Slesnick et al. 2006b), and solar system objects (Brown et al. 2005), among other phenomena.

The data were taken over a span of about 3.5 years using the QUEST2 Large Area Camera on the Samuel Oschin Schmidt 48″ telescope at Palomar Observatory. The camera, built specifically for this survey, has a $3°.6 \times 4°.6$ field of view populated with 112 CCDs. The CCDs are arranged in 4 rows by 28 columns such that a different filter can be placed over each row. In driftscan mode, an 8 hr scan will yield about 500 deg^2 of data with successive ∼140 s exposures in the four filters. Two filter sets were used during the survey: Johnson UBRI and Gunn $r'i'z'z'$. Details of the camera are presented in Baltay et al. (2007).

PQ's area coverage includes declinations from $-25°$ to $+25°$, and all right ascensions further than $15°$ from the galactic plane. The amount of time between observations over the same coordinates ranges from several hours to the length of the survey; typically an area is covered twice in one lunation and revisited each year. On average, there are roughly five observations of the entire survey area in each filter set. Certain regions have been examined more often for either calibration reasons or specialized analyses, yielding up to 25 observations for a small fraction of the area.

The survey comprises about 15 terabytes of image data, which have been processed with multiple pipelines. The Yale pipeline, used in this work, performs object detection, astrometry, photometry, and associates detections of the same object across the four rows of chips (or, equivalently, the four color filters). Photometric calibrations correct for sensitivity variations within each chip and between different chips, including the effects of nonlinearities in some CCDs. The survey has amassed its large data set by observing in non-photometric conditions. Extinction corrections calibrate the data to the level of the best PQ scan over each square degree, which is assumed to be photometric. This processing software and standard calibration of the data are described in detail in Andrews et al. (2008).

An additional, relative calibration is done before using the data for variability work. The goal of the relative calibration is not to determine most accurately an object's magnitude, but for each individual measurement of an object to be as consistent with each other measurement as possible. The extinction correction is therefore eliminated in favor of a routine that calibrates the data to the most phometrically stable scan rather than the one in which the stars appear brightest. An additional correction is made to account for spatially dependent variations in the data due to effects like scattered light in the camera. Finally, strict quality cuts are implemented to eliminate calibration tails due to noisy data, poor measurements of objects that do not conform to the point-spread function (PSF) profile, or rare catastrophic failures of the processing software. In order to generate as many comparable measurements of an object as possible, we calibrate the Johnson R and SDSS r′ measurements, and similarly the Johnson I and SDSS i′ measurements, together to obtain combined data which we call Rr and Ii bandpasses. The result of the relative calibration is a systematic error of 0.7% for the Rr data, and 1.3% for the Ii′ data. The relative calibration procedure is discussed and evaluated in detail in Bauer et al. (2009a). The relatively calibrated PQ data are used for the variability work in this paper. The standard calibration, in which each of the Johnson and SDSS filters is calibrated to be photometric, is used when studying average colors of the objects.

3. SELECTION CRITERIA

3.1. Variability Cut

Blazars exhibit high amplitude variability on all timescales probed by the PQ Survey. Their appearance in the survey is examined in detail in Bauer et al. (2009b), which examines the ensemble optical variability of 276 FSRQs and 86 BL Lacs taken from a variety of sources: Stickel et al. (1991), Hewitt et al. (1993), Collinge et al. (2005), Donato et al. (2005), Sowards-Emmerd et al. (2005), Veron-Cetty & Veron (2006), Massaro et al. (2007), Turriziani et al. (2007), and Healey et al. (2008). The structure function, variability amplitudes over different time lag ranges, and duty cycles of these objects are studied in order to characterize the behavior of blazars in large-scale variability surveys such as PQ. Because blazars vary dramatically on all measured timescales, we do not impose frequency-dependent selection criteria when compiling the sample. Instead, we simply select all objects that vary by more than 0.4 mag between any two epochs of observation. A separate search is underway at Caltech for objects that are highly variable on short timescales (∼1 hr to a few days); this work will be presented in a later paper.

Our specific cut of 0.4 mag is motivated by the comparisons made between type I quasars and blazars in Bauer et al. (2009b). Figures 3 and 4 in that work show the fluctuation amplitudes of these AGN classes as seen in the PQ Survey over a variety of timescales. At all timescales measured, quasar fluctuations are infrequent at amplitudes greater than a few tenths of a magnitude, while the blazar sample includes a significant tail out to larger amplitudes. In order to select jet-based blazar fluctuations rather than quasar-like behavior due to accretion disk flares, we impose a variability cut at 0.4 mag. To exclude cases of calibration error, we insist that both the Rr and Ii data must show a magnitude change of at least 0.4 mag in the same direction between the two epochs.

Figure 1 describes the variability of several types of objects in the PQ data. The X-axis is the maximum magnitude jump seen by each object between any two epochs. The jump must be significant to 3σ in both the Rr and Ii bands in order to be included in the histogram. The thin solid line describes the variability seen in a random subset of 194,000 relatively calibrated PQ objects. The thick solid line denotes 14,800 type I quasars spectroscopically identified by the SDSS (Abazajian et al. 2008). The dashed line shows the behavior seen in blazars, using a sample of 425 collected in Bauer et al. (2009b). (We do not insist on redshift measurements for these objects, allowing us to use more blazars from the surveys sampled by Bauer et al. 2009b than were used in the paper's main analysis.) The three samples' histograms are each normalized to a total of 1000 objects in order to be easily comparable.
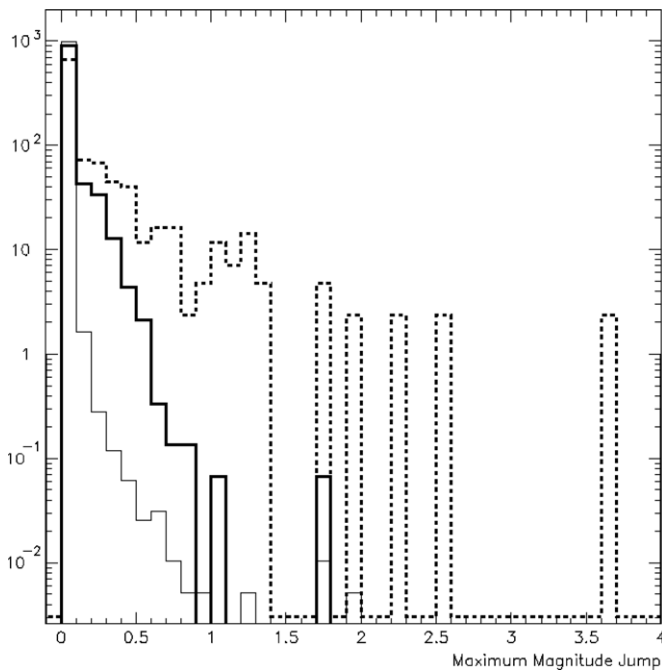
Figure 1. Maximum magnitude jump for different object types: a random sample of PQ objects (thin solid line), quasars (thick solid line), and blazars (dashed line). The jump must be significant to 3σ and seen in both Rr and Ii bands.

Because we only see roughly four epochs for each object, the light curves for each object are sparsely sampled. There could easily be variability that we do not observe. This observation is supported by the fact that although variability is considered a fundamental property of blazars, we only see variability in about 35% of the sample using the criterion of 3σ fluctuations in both bandpasses. Of the blazars for which we do see variability, 40% fluctuate by more than 0.4 mag. Therefore 14% of the blazar sample is selected by a variability cut at 0.4 mag. In comparison, 0.7% of the quasar and 0.02% of the random samples are selected by the same cut. This variability criterion will clearly not include all blazars observed by PQ; instead, it is intended to be as efficient as possible in selecting blazars using a method that is not affected by radio or X-ray biases.

3.2. Auxiliary Cuts

Many types of objects are known to be variable; therefore our primary cut will accept more than simply AGNs. We expect to see periodic variables, for example, due to geometric effects as in eclipsing binary systems, or due to pulsations as in RR Lyrae. We also expect to see aperiodic variables such as flaring M dwarfs or red giants. We will select episodic variables as well, for example, supernovae or cataclysmic variables (CVs). Two cuts, independent of variability amplitude, are made in order to eliminate a large fraction of the expected background. The number of objects eliminated by these cuts is discussed in Section 5.

3.2.1. Timescale of Observation

We do not have sufficient light curve information to distinguish between periodic variables and aperiodic ones such as AGN. However, we can eliminate episodic variables by requiring the objects to have been detected over a span of at least 200 days. This requirement will not be met by the violent explosions of supernovae and many CVs, which have timescales on the order of a few months or less.

3.2.2. Galactic Latitude

Main-sequence stars in eclipsing binary systems, red giants, RR Lyrae, and CVs are all faint enough such that the vast majority that are bright enough to see are in our galaxy. Therefore, looking at sky positions far from the plane of the galaxy significantly reduces our stellar contamination. Some of these objects are also seen at high galactic latitudes; for example, RR Lyrae are often studied in the galactic halo (e.g., Vivas et al. 2006). For the purpose of finding mainly AGNs, we restrict our search to latitudes more than $40°$ away from the galactic plane. This is a very strict cut; there are undoubtedly interesting objects to be seen closer to the galactic plane. We leave the examination of lower galactic latitudes until we better understand the current, high latitude sample.

3.3. Color Classification

We expect the variable sample to include stars from the galactic halo. Color information can be used to identify common stellar types in the sample.

One approach to making color cuts could be to keep the variable objects that have colors similar to known blazars. However, the optical colors of blazars depend on the central frequencies of the objects' SED peaks. Previously discovered blazars may have these frequencies biased by the fact that the objects were found in the radio and/or X-ray bands. If we wish to select a blazar sample independent of radio and X-ray biases, we cannot apply color cuts that are based on the colors of radio and X-ray-selected blazars. For this reason we do not select objects based on the similarity of their colors to those of known blazars. Instead, we rank objects as poor if they have colors similar to common stars. It may be true that many interesting objects in the sample, including blazars, have colors close to stellar. However, by downgrading objects with stellar colors we can decrease the contamination of our best blazar sample and usefully rank the objects for future follow-up study.

To identify stellar variables we fit the PQ data, plus color information from other large-area surveys, to templates of typical stars. If an object's colors fit well to a template then it is assumed to be a star. To get the widest wavelength range of data with which to make comparisons, we compile all available PQ UBRIriz (determined using the absolute calibration), SDSS ugriz (data release 5; see Adelman-McCarthy et al. 2007), *Galaxy Evolution Explorer* (*GALEX*) fn (data release 3; see Martin et al. 2005), and 2MASS JHK measurements (Skrutskie et al. 2006) of the variables. The spectral templates published by A. J. Pickles (Pickles 1998), which span wavelengths of 1150–12500 Å, are convolved with the transmission curves of the various surveys and fitted to the broadband measurements.

The ability of the color fits to identify stars depends on the amount of information available for each variable candidate. *GALEX* and SDSS do not cover all of the PQ sky area, so some of the PQ variables have more color information than others. Consequently, the color fit assigns stellar status more accurately for some objects than for others.

To study this effect, sample subsets of all PQ objects, known quasars, known blazars, and the PQ variables were divided into groups based on the availability of data for each object. Different permutations of available SDSS, *GALEX*, and 2MASS data yield eight possible coverage combinations. For each coverage combination, the objects were run through the template fitting, and a χ^2 cut was chosen that best balanced the cut's completeness in selecting AGNs with the purity of the resulting

Table 1
Color Cut Statistics for Different Coverage Combinations

Coverage	χ^2 Cut	Sample	Quasars	Blazars	Variables	Cat.
Q + S + G + 2	3.0	23% (1271)	86% (1282)	100% (21)	30% (126)	A
Q + S + G − 2	2.4	11% (1817)	86% (7434)	100% (30)	52% (342)	B
Q + S − G + 2	2.8	14% (15261)	85% (1388)	100% (107)	29% (438)	C
Q + S − G − 2	2.2	5% (42643)	78% (9211)	98% (194)	37% (974)	D
Q − S + G + 2	2.0	69% (1271)	82% (1282)	100% (27)	59% (128)	E
Q − S − G + 2	2.0	52% (15261)	75% (1388)	97% (91)	50% (358)	F
Q − S + G − 2	2.0	9% (1817)	25% (7434)	92% (36)	28% (577)	G
Q − S − G − 2	2.0	12% (42643)	20% (9211)	82% (159)	23% (976)	H

Notes. Q, PQ; S, SDSS; G, *GALEX*, 2, 2MASS. Q − S + G − 2 indicates objects for which there is PQ and *GALEX* data, but no SDSS or 2MASS data. For each type of object (a random sample of PQ objects, SDSS spectroscopic quasars, known blazars, and PQ variables), what percentage pass the chi squared cut (i.e., look non-stellar)? In parentheses is the total number of objects used in the calculation; note the lower statistics for blazars. Each coverage category is given a label from A to H, roughly in order corresponding to the quality of the cut.

sample. The number of objects tested and the percentage whose colors look non-stellar are given in Table 1. If the color fitting perfectly reflects the object type, the representative sample should have a small percentage with non-stellar colors, while the quasars and blazars should appear entirely non-stellar. The variable sample, assuming it is made up largely of AGNs but also includes variable stars, should be somewhere in between. As seen in Table 1, the ability to distinguish the object types clearly varies with the amount of available color data.

These percentages are helpful quantities because known quasars and blazars are examples of highly variable objects which we would like to find. However, they are not perfectly indicative of the ability of the color cut to pick out interesting objects in the list of variables. For example, there are more types of interesting objects in the sample than just UV excess selected quasars (which dominate the quasar sample) and radio and X-ray-selected blazars (which dominate the blazar sample). Furthermore, not all desired objects are treated equally by the cut, as shown by the fact that the quasar and blazar statistics give different results from each other. For example, the SDSS u' filter is critical in separating the low-redshift quasars from the main sequence, and therefore SDSS coverage makes a very large difference in the quasar percentage kept by the cut. However, SDSS coverage makes a much smaller difference for the blazar sample.

To aid in the ordering of candidates for follow-up, we divide the variables into eight coverage categories, A through H. In our letter assignment we adopt the philosophy that more information is better, given the consideration that we do not know the details of how the color cuts treat all types of AGNs. Objects in category A are covered by all four surveys, while those in category H are seen only in PQ. The results given in Table 1 determine the ordering of the categories in cases where there is coverage by the same number of surveys, but different combinations (like cases B and C). Each object is therefore described by its coverage (A through H) and its color classification (pass or fail), where the variable passes the classification if it looks non-stellar.

4. EXPECTED SOURCE AND BACKGROUND COUNTS

The prevalence of variable stars depends strongly on the flux limit of one's data. To date there have been very few studies of the variability of large, heterogeneous samples of objects, therefore the characteristics of overall stellar variability, including how it scales with survey depth, are not well understood.

The Faint Sky Variability Survey (FSVS) (Morales-Rueda et al. 2006) and the SDSS (Sesar et al. 2007) have both studied the variable fraction of main-sequence stars. While their flux limits are fainter than ours, we can use their results as a rough estimate of the background we should expect.

The FSVS saw that 1% of the main-sequence stars are variables, on timescales shorter than about 10 days, by at least 0.01 mag. Furthermore, they noted that 0.07% of the main-sequence stars vary by more than 0.25 mag, and 0.02% vary more than 1 mag. The SDSS saw that 0.5% of the main-sequence stars are variable, on timescales up to about five years, by at least 0.05 mag.

About 85 million objects pass the PQ relative calibration quality cuts and are examined for variability. Assuming the above statistics, and assuming the PQ objects are dominated by main-sequence stars, we should expect to see about 425,000 main-sequence objects varying by at least 0.05 mag. Between 17 and 60 thousand quickly varying main-sequence stars (on timescales less than 10 days) should pass our variability cut of 0.4 mag. Sparse light curve sampling will cause us to see sufficient variability in only a fraction of this number, around 15% if our scanning cadence is equally suited for observing variability in stars and blazars. This leaves us with the expectation of seeing between 2500 and 9000 main-sequence variables over the entire 15,000 deg^2 of the survey.

In order to preferentially remove variable stars from our sample, we eliminate objects fewer than 40° from the galactic plane. At the typical magnitude of the variables, this cut should reduce the stellar contribution by a factor of ∼13 (Zombeck 1990). In our final search area, therefore, we expect to select between roughly 190 and 700 main-sequence variable stars.

The number density of blazars is not well known, but work on a deep sample of blazars (Padovani et al. 2007) estimates 0.6 deg^{-1} for FSRQs and 0.06 deg^{-1} for BL Lacs down to a 5 GHz flux of 50 mJy. It is not clear how the optical flux of these blazars relates to the radio flux limits used in the study. However, if all of these blazars are above our optical flux limit, we would expect to find about 10,000 over the whole survey, or 4800 over the high galactic latitude area considered.

5. RESULTS

Over the entire PQ sky area of 15,000 deg^2, 14,185 objects pass the variability cut of 0.4 mag. Of these, 10,838 have been seen over a timespan of at least 200 days, and therefore are not

Table 2
Identification Summary for Known QUEST Variables

Object Type	Number
BL Lac	18
FSRQ	8
QSO	119
QSO and radio source	23
QSO and radio and X-ray source	4
QSO and X-ray source	15
Radio source	78
X-ray source	32
Radio and X-ray source	22
UV excess QSO candidate	76
UV excess QSO candidate and radio source	3
Variable object	15
RR Lyra	38
Carbon star	26
Star	65
Galaxy	15
Total identified objects	557
Total AGNs	187
Total probable AGNs	211
Total other known variables	79
Total other known objects	80

Table 3
Color Classifications for Known AGNs and Stars in the Variable Sample

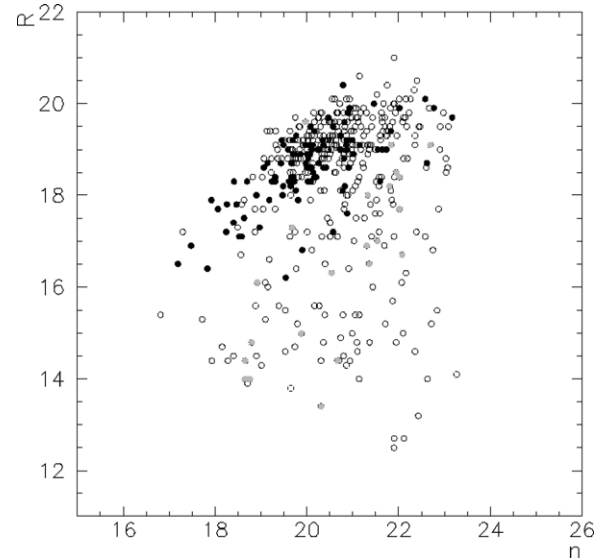| Object Type	Color Category	% Pass	# Total
AGN	A	100	8
	B	74	62
	C	73	15
	D	75	75
	E	100	4
	F	43	7
	G	50	10
	H	33	6
	All	72	187
Star	A	7	15
	B	19	16
	C	27	11
	D	15	20
	E	0	0
	F	0	0
	G	50	2
	H	0	1
	All	17	65

Figure 2. Average Johnson R magnitude vs. *GALEX n* magnitude. Variables in color classes PASS_A through PASS_D with *GALEX* measurements are shown as hollow circles. Known AGNs are filled in black. Known stars are filled in gray.

short-timescale transients. (None of the blazars in the set of 425 collected in Bauer et al. (2009b) is removed from the sample by this cut.) A subset of 3955 lie more than $40°$ away from the galactic plane, and so are less likely to be variable stars. The 3955 variable candidates have been examined by eye to eliminate those that are clearly contaminated by artifacts or are extended galaxies that are likely mismeasured by the PSF photometry software. There are 842 apparent cases of poor data, for example, if the light curves show a single outlier corresponding to R and I images on bad chip areas. This leaves 3113 variables in the final sample.

Of the 3113 variables, 557 have been previously identified by other surveys. Table 2 summarizes the identifications. Table 2 also gives the total number of identified AGNs, probable AGNs (including radio sources, X-ray sources, and color-selected quasar candidates), other known variables, and remaining identified objects (not known to be variable). These IDs have been collected mainly using NED[4] and SIMBAD.[5]

As well as collecting information from the literature, we have initiated a program of spectroscopic identifications of these sources at the Palomar 200″ telescope. To date, a few tens of objects have been observed, with roughly a half being AGNs, and a half being CVs and other types of variable stars. Among the AGNs, there is roughly an equal number of probable blazars (with featureless blue continuum spectra) and broad emission line quasars, most of which have radio source counterparts in NED and are thus likely FSRQ. A detailed discussion of these observations will be presented in a forthcoming paper.

A measure of the success of the color classification is shown in Table 3, which gives the color categories and classifications for PQ variables that are identified in the literature as stars and AGNs. Of known AGNs, 72% pass our color cut, i.e., have non-stellar colors. Of known stars, only 17% pass the cut. The table also shows that the color categories with more surveys' information yield more accurate results, as expected.

The statistics are quite low, but this is a useful assessment of the accuracy of the classifications for our variable sample.

The PQ variables are available at http://webvoy.cacr.caltech.edu/CasJobs in the PQVariables1 table in the QuestProducts database. The table fields are described in detail in the Appendix. PQVariables1 includes, along with the position of the objects, the maximum 3σ significant magnitude jump seen between any two epochs in both the Rr and Ii data. The main selection criterion for the PQ variables is that this value must be greater than 0.4. Also given is the rms of the relatively calibrated Rr magnitudes of the object, and how many Rr measurements were available. Typically there are the same number of Rr and Ii measurements. The average Johnson R magnitude of the object, measured using the standard calibration, is also provided. The color classification of the object is listed, as well as its coverage category, as described in Section 3.3. PASS means that the object *does not* have stellar colors. As well as this information

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Table 4
Description of the PQVariables1 Table in the QuestProducts Database

Column Name	Description
ra	Right ascension in J2000 degrees
dec	Declination in J2000 degrees
delta_mag	The maximum magnitude jump seen between any two epochs. To be significant, the jump must be seen in both Rr and Ii bands; the smaller of the two bands' magnitude change is given here.
R_sigma	Rr magnitude sigma
n_obs	Number of Rr observations. The number of Ii observations is typically the same
R_mean	Mean Johnson R magnitude
color_class	The results of the stellar spectral template fitting. PASS means the object does not have stellar colors. A through H indicate the amount of color data available for the fit, with A yielding the most reliable results
notes	Information taken from other data sets.
redshift	Redshift, taken from other data sets
redshift_err	Redshift error
FIRST	1.4 GHz flux, in mJy, from the FIRST Survey (Becker et al. 1995)
FIRST_err	1.4 GHz flux error, in mJy, from the FIRST Survey
NVSS	1.4 GHz flux, in mJy, from the NVSS (Condon et al. 1998)
CRATES_4.8	4.8 GHz flux, in mJy, from the CRATES Survey (Healey et al. 2007)
CRATES_8.4	8.4 GHz flux, in mJy, from the CRATES Survey
2MASS_K	K magnitude from the 2MASS (Skrutskie et al. 2006)
2MASS_err_K	K magnitude error from the 2MASS
2MASS_H	H magnitude from the 2MASS
2MASS_err_H	H magnitude error from the 2MASS
2MASS_J	J magnitude from the 2MASS
2MASS_err_J	J magnitude error from the 2MASS
UKIDSS_K	K magnitude from the UKIDSS (Lawrence et al. 2007)
UKIDSS_err_K	K magnitude error from the UKIDSS
UKIDSS_H	H magnitude from the UKIDSS
UKIDSS_err_H	H magnitude error from the UKIDSS
UKIDSS_J	J magnitude from the UKIDSS
UKIDSS_err_J	J magnitude error from the UKIDSS
UKIDSS_Y	Y magnitude from the UKIDSS
UKIDSS_err_Y	Y magnitude error from the UKIDSS
GALEX_n	n magnitude from the *GALEX* (Martin et al. 2005)
GALEX_err_n	n magnitude error from the *GALEX*
GALEX_f	f magnitude from the *GALEX*
GALEX_err_f	f magnitude error from the *GALEX*
ROSAT	0.1–2.4 keV counts per second from the *ROSAT* (Voges et al. 1999)
ROSAT_err	0.1–2.4 keV counts per second error from the *ROSAT*
XMM	0.2–12 keV erg s^{-1} cm^{-2} flux from the *XMM* (Jansen et al. 2001)
XMM_err	0.2–12 keV erg s^{-1} cm^{-2} flux error from the *XMM*
QSO	Flag: Has the object been identified as a QSO? Further information in the notes field.
carbon_star	Flag: Has the object been identified as a carbon star? Further information in the notes field.
RR_Lyra	Flag: Has the object been identified as an RR Lyra? Further information in the notes field.
BL_Lac	Flag: Has the object been identified as a BL Lac? Further information in the notes field.
FSRQ	Flag: Has the object been identified as an FSRQ? Further information in the notes field.

from the PQ Survey, the database provides available information from surveys at other wavelengths. Fluxes are provided in radio, infrared, UV, and X-ray wavelengths for subsets of the variables with such measurements in the FIRST (Becker et al. 1995), NVSS (Condon et al. 1998), CRATES (Healey et al. 2007), 2MASS, UKIDSS (Lawrence et al. 2007), *GALEX*, *ROSAT* (Voges et al. 1999), or *XMM* (Jansen et al. 2001) surveys. The fact that these objects each vary by more than 0.4 mag in optical wavelengths complicates careful color analyses of these objects. However, flux information from a large variety of wavelengths can give rough information about the objects' SEDs, and therefore be of interest when selecting certain kinds of candidates for follow-up. Conversely, data over a large wavelength range can provide insight into the physical processes of those candidates with secure identifications. For example, it would be interesting for the Fermi Gamma-Ray Space Telescope to measure the typical gamma-ray flux emission from blazars

in this sample as opposed to objects selected in the standard manner.

As an example of how multiwavelength information can aid in further classifying the candidates, Figure 2 shows the average Johnson R magnitude of the variables versus *GALEX n* magnitude, for those with good color classification and *GALEX* measurements. The variables in color categories A through D with colors unlike the stellar templates are shown as hollow circles. Those objects already known to be AGNs are filled with black, while those identified as stars are filled with gray. The known AGNs are bright in n while faint in R; the majority of the variables overlap the AGN distribution. Known stars have similar n measurements but are brighter in R. The bright-R objects are most likely not main-sequence variables, however, because of their color classifications. Broad wavelength information is clearly helpful in characterizing the variables. For the objects with no such data, however, the

Table 5
Explanation of Abbreviations in the PQVariables1 Table

Abbreviation	Reference
QUESTII	The Palomar-QUEST Survey
QUEST1	The QUEST1 Variability Survey (Rengstorf et al. 2004)
1 Jansky	A Complete Sample of 1 Jansky BL Lacs (Stickel et al. 1991)
2QZ	The 2DF QSO Redshift Survey (Croom et al. 2001)
APMUKS	The APM Galaxy Survey (Maddox et al. 1990)
BB93	Beauchemin & Borra 1993
BF80	Berger & Fringant 1980
CGCS	Carbon Stars discovered by the SDSS (Margon et al. 2002)
EDCSN	The ESO Distant Cluster Survey (White et al. 2005)
DWS	A Catalog and Atlas of CVs (Downes et al. 1997)
FASTT	Variables in the SDSS Calibration Fields (Henden & Stone 1998)
FBQS	FIRST Bright Quasar Catalog (White et al. 2000)
GAMMA1	Gamma-Ray Blazars (Sowards-Emmerd et al. 2005)
HE	The Hamburg/ESO Survey (Christlieb et al. 2005)
Kukarkin	ID List of Variables Nominated in 1968 (Kukarkin et al. 1968)
M53	IDs of Stars in the Globular Cluster M53 (Rey et al. 1998)
JVAS	The Jodrell Bank VLA Astrometric Survey (Browne et al. 1998)
PUL3	The Pul-3 Catalogue of 58483 Stars in the Tycho2 system (Khrutskaya et al. 2004)
LBQS	The Large Bright Quasar Survey (Hewett et al. 1995)
MAPS-NGP	The MN Automated Plate Scanner Catalog of the North Galactic Pole (Cabanela et al. 2003)
Mauron	Cool Carbon Stars in the Halo (Mauron et al. 2004)
Meinunger	RR Lyrae-type stars in Sonneberg fields (Meinunger 1977)
MIP	McIntosh et al. 2004
Palomar 13	IDs of Stars in the cluster Palomar 13 (Blecha et al. 2004)
PKS	Parkes Catalog (Wright et al. 1990)
ROSAT	The Roentgen Satellite (Voges et al. 1999)
Siegel	RR Lyrae stars in Bootes (Siegel 2006)
SDSS	The Sloan Digital Sky Survey (Adelman-McCarthy et al. 2008)
SDSS	Candidate RR Lyrae found in the SDSS commissioning data (Ivezic et al. 2000)
VCV	The Veron-Cetty & Veron Catalogue of Quasars and Active Nuclei (Veron-Cetty & Veron 2006)
Vivas	The QUEST RR Lyrae survey (Vivas et al. 2004)

PASS/FAIL color classification scheme summarizes the available information using just optical measurements.

6. CONCLUSIONS

We have examined 7200 deg^2 of relatively calibrated, high galactic latitude data from the PQ Survey and compiled a list of 3113 of the most variable objects seen. Specifically, these objects have been observed to vary by more than 0.4 mag simultaneously in two bandpasses, over any timescale probed by the survey (from hours to 3.5 years). We insist that the variable candidates have been detected by the survey over a span of at least 200 days in order to eliminate transients from the sample, and we have examined the objects by eye to eliminate those that appear variable due to obvious data artifacts. To try to identify variable stars in the sample we have compared the objects' colors to spectral templates of common stellar types. The 3113 variables are thereby grouped into subclasses according to the similarity between their colors and those of the templates. Although there may be blazars, or other interesting objects, with colors similar to common stars, the non-stellar color classes will be the purest samples of AGNs and therefore perhaps the highest priority for follow-up. The catalog is available at http://webvoy.cacr.caltech.edu/CasJobs, in the PQVariables1 table in the QuestProducts database. The contents of the catalog are described in Appendix A.

The search for highly variable objects in the PQ Survey is motivated by the desire to select a large sample of blazars.

An optical variability-based blazar search has not previously been carried out on this scale; these rare AGNs are typically found through their X-ray and/or radio emission. Current blazar samples are most likely influenced by selection effects related to the wavelength of their discovery; those discovered in radio wavelengths tend to be LBLs, with lower frequency emission, while X-ray-discovered blazars tend to be HBLs. A sample found with optical selection effects and without color biases may include objects significantly different from those currently discovered, both in the frequency range of the emission and in the overall SED shape.

Although wide area sky surveys are becoming more common, the time domain remains relatively unexplored. It is not understood what a large variability-selected sample of objects may hold. We have compiled a highly variable sample with the aim of selecting blazars; however all of the objects have exhibited dramatic variability that is very rare and deserves further study. We hope that current and future surveys will observe these PQ variables in order to improve our understanding of the physical mechanisms behind violent variability.

APPENDIX

DESCRIPTION OF THE PQVARIABLES1 DATABASE TABLE

The PQVariables1 table is part of the QuestProducts database at http://webvoy.cacr.caltech.edu/CasJobs. Table 4 describes the contents of PQVariables1. Table 5 explains the abbreviations used in the database table.

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