

# Exploring the Time Domain with the Palomar-QUEST Sky Survey

A. Mahabal<sup>a</sup>, S. G. Djorgovski<sup>a</sup>, M. Graham<sup>a</sup>, R. Williams<sup>a</sup>,  
B. Granett<sup>a</sup>, M. Bogosavljevic<sup>a</sup>, C. Baltay<sup>b</sup>, D. Rabinowitz<sup>b</sup>,  
A. Bauer<sup>b</sup>, P. Andrews<sup>b</sup>, N. Morgan<sup>b</sup>, J. Snyder<sup>b</sup>, N. Ellman<sup>b</sup>,  
S. Duffau<sup>b</sup>, J. Musser<sup>c</sup>, S. Mufson<sup>c</sup>, M. Gebhard<sup>c</sup>,  
R. Brunner<sup>d</sup> and A. Rengstorf<sup>d</sup>

<sup>a</sup>*California Institute of Technology, Pasadena, CA 91125*

<sup>b</sup>*Yale University, New Haven, CT 06520*

<sup>c</sup>*Indiana University, Bloomington, IN 47405*

<sup>d</sup>*NCSA/UIUC, Champaign, IL 61820*

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## 1 Introduction

Discoveries in astronomy are often made through a systematic exploration of previously poorly covered regions of the observable parameter space [1,2]. In particular, exploration of the time variability on the sky over a broad range of flux levels and wavelengths is rapidly becoming a new frontier of astronomical research [3,4]. Many exciting astrophysical phenomena are known in the time domain: all manner of variable stars, stellar explosions such as SNe and GRBs, variable AGN, pulsars, microlensing events, etc. Yet undoubtedly many more remain to be discovered.

A number of surveys and experiments exploring the time domain are already in progress (see, e.g., [5,6] for listings), and even more ambitious synoptic sky surveys are being planned, e.g., [7,8]. The important factors in such programs are (1) the area covered, (2) the depth of coverage, (3) number of wavelengths used, and (4) the baseline(s) in time.

We conducted an exploratory search for highly variable objects [9] and optical transients [10] using  $\sim 8000 \text{ deg}^2$  in the NGP and SGP areas of the Digital Palomar Observatory Sky Survey (DPOSS) plate overlap regions. The effective depth of these searches was  $r_{max} \approx 19$  mag for the “high” states, with a plate limits  $r_{max} \approx 21$  mag. Time baselines ranged from days to years, with  $\sim 2$  yrs being typical. After eliminating various artifacts and contaminants,

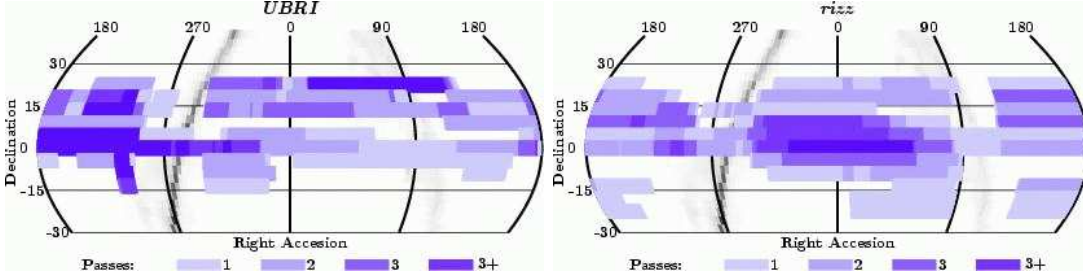


Fig. 1. Palomar-QUEST coverage as of June 2004:  $\sim 5000 \text{ deg}^2$  have been covered at least twice in *UBRI* and  $\sim 5500 \text{ deg}^2$  at least twice in *r'iz'z'*.

and applying well defined statistical criteria for selection, we identified a large number of highly variable objects, and followed up spectroscopically a subset of them at the Palomar 200-inch telescope. They turned out to be a heterogeneous collection of flaring M-dwarfs, OVV QSOs and BL Lacs, CVs (including a rare magnetic one), and some otherwise non-descript stars. Approximately a third to a half of all highly variable objects down to this magnitude level, at moderate and high Galactic latitudes appear to be associated with AGN.

We also found a number of optical transients (operationally defined as high-S/N, PSF-like objects, detected only once). We estimate that a single-epoch “snapshot” down to this flux level contains up to  $\sim 1000$  transients/sky. Their nature remains unknown, but in at least 2 cases deep follow-up imaging revealed apparent faint host galaxies, which now await spectroscopy.

This pilot study gave us some hints as to what may be expected in a dedicated, wide-field, synoptic sky survey at comparable magnitudes. The faint variable sky has a very rich and diverse phenomenology.

In this paper, we describe briefly a new, large, digital synoptic sky survey, Palomar-QUEST (hereafter *PQ*); a more detailed description of the survey will be presented elsewhere.

## 2 The Palomar-QUEST Sky Survey

The Palomar-Quest synoptic sky survey, a collaborative project between Yale, Caltech, and NCSA (some other groups are also involved in more specific collaborations) is a new major digital sky survey conducted at the Samuel Oschin 48-inch Schmidt telescope at Palomar. The survey uses a special 112-CCD, 162-Megapixel camera built especially for this purpose. Some of the salient features of the survey are: (1) Data taking in the Point-and Stare (PS) mode, covering  $\sim 9.2 \text{ deg}^2$  per exposure, or in a Drift Scan (DS) mode, in strips  $4.6^\circ$  wide, with a typical coverage of  $\sim 500 \text{ deg}^2/\text{night}$ , (2) Near simultaneous observations in one of two filter sets in the DS mode: Johnson-Cousin’s *UBRI*

or SDSS  $r'i'z'z'$ , (3) In good conditions, typical limiting magnitudes for point sources:  $R_{lim} \approx 22$  mag,  $I_{lim} \approx 21$  mag, (4) In the DS mode, useful Declination range  $-25^\circ < \delta < +30^\circ$ , for a total anticipated survey area of  $\sim 12,000 - 15,000 \text{ deg}^2$ , (5) Multiple-pass coverage, with at least 4 passes per year at each covered location, (6) Time baselines for repeats ranging from days to months, anticipated to extend to multi-year time scales over the next 3 to 5 years or beyond, (7) NVO standard, protocols, and connections built in from the start.

The survey has started producing a steady stream of science-grade data, from summer of 2003. In the DS mode, it typically generates  $\sim 1$  TB of raw image data per month (assuming  $\sim 14$  clear nights). This unprecedented amount of data makes this the largest synoptic survey of its kind both in terms of area covered and depth. A broad range of science is envisioned for the survey, but exploration of the time domain will be one of the main focal areas.

### 3 Toward Real-Time Transient Detections

The existing  $PQ$  pipeline is geared to complete processing of a night's data by the next day. In a matter of hours catalogs become available in the four filters used and can be integrated and combined with other epochs available for the area covered that night. This is sufficient for most  $PQ$  projects, including those involving variable objects, e.g. SNe. However, such a turn-around time can be too slow for the follow-up of rapidly fading sources and transients. Thus, we have started work on a real-time processing pipeline which will enable detections of such sources within minutes or less.

We will be comparing nightly catalogs with older catalogs from  $PQ$  itself, as well as other surveys and archives, using NVO infrastructure and methodology. Positions of possible transients will be compared with those of known variable sources, known asteroids, etc. Our goal is to provide detections of potentially exciting sources in real-time, via email alerts and a dedicated website. Given the large area coverage of  $PQ$  (Figure 1 shows coverage current as of June 2004) and the results from our exploratory DPOSS project noted above, we estimate that we will be detecting up to several tens of highly variable or transient sources per night. A key challenge will be to deal with this abundance of data in an effective manner – maintaining a high completeness in terms of the interesting variable and transient sources discovered, while maintaining a low contamination rate by spurious or uninteresting sources – and doing it in real time. A number of advanced statistical and Machine Learning techniques will be explored to this end.

We believe that  $PQ$  will provide a major new window into the faint variable sky at optical wavelengths over the next several years. At the same time, this

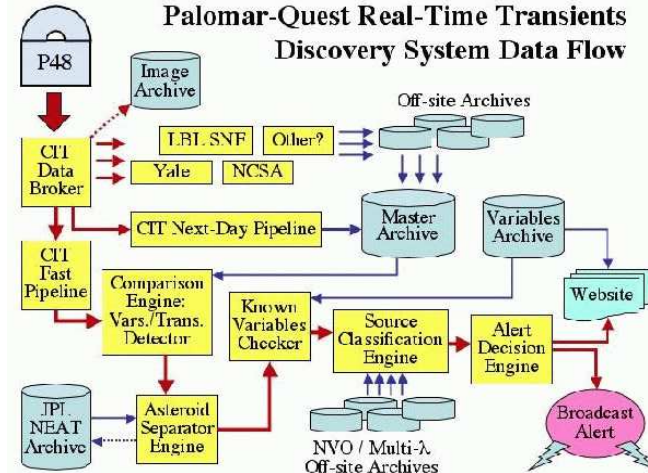


Fig. 2. A schematic outline of a real-time data reduction pipeline which would enable a rapid discovery and spectroscopic follow-up of transients and other interesting objects. Particular emphasis will be on eliminating spurious or relatively uninteresting candidates, in order to keep the number of real-time alerts reasonable, while not missing any interesting ones. The actual design of this system is still in progress.

survey will serve as a science, technology, and methodology precursor for the more ambitious future projects such as LSST [7] or Pan-STARRS [8].

## References

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