The Palomar-Quest (PQ) Survey: The Science Case

A description from our successful NSF AST proposal

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3.1 The Large QSO Survey. The principal effort of the Yale group is a search for QSOs using both colors and variability as selection criteria. Different combinations of $UBRIriz$ colors can be used to select QSOs out to $z \sim 6$, with a majority at $z \sim 2 \pm 1$. Variability is essentially redshift-independent selection method. For a demonstration of the methodology, see, e.g., Rengstorff et al. (2003). Over the survey area of 15,000 deg$^2$, we expect to detect $\sim 300,000$ QSOs down to our flux limits. We plan to obtain spectroscopic redshifts for $\sim 1,000$ of them, mainly to calibrate the selection functions and photometric redshifts (which we believe we can estimate from colors with a typical accuracy $\Delta z \approx 0.2$). We note that many of the 2dFQz survey spectroscopically identified QSOs, as well as many QSOs from SDSS and other surveys will be within our area; we will make a full use of this external information. The resulting unprecedented QSO sample will be used for several projects, as follows:

3.2 QSO Gravitational Lensing as a Cosmological Tool. The primary goal of the Yale group will be to discover a sample of a few hundred strong lenses from the large QSO sample; recall that the probability for strong lensing in QSO samples at comparable magnitudes is $\sim (1-2) \times 10^{-3}$. From our experience in the Venezuelan survey we believe that we can find strongly lensed QSOs down to separation angles of $\sim 1.5$ arcsec. We are planning several studies with this large sample of lenses:

(a) A measurement of the lensing probability $p(z)$. In principle this function is very sensitive to the cosmological parameters $\Omega_0$, $\Lambda_0$, and the dark energy equation of state parameter $w(z)$. There is, however, some uncertainty about how well the systematic uncertainties due to the distribution of dark matter in galaxies and larger structure, the merging history of dark halos, etc., can be kept under control, and thus the precision and reliability with which the cosmological parameters can be obtained from this method. However, this approach does provide an independent and thus very valuable “sanity check” on the currently popular methods based on the CMBR, SNe, and LSS.

(b) If, on the other hand, we assume the cosmology derived from other measurements, we can then provide valuable new constraints on the evolution of the mass distribution as a $f(z)$.

(c) We expect that some fraction of the newly found lenses will have geometry which implies a simple and understandable mass distribution. Their monitoring for variability and time delays can provide an independent estimate of the far-field Hubble’s constant.

Figure 2. Lensing probability as a function of redshifts for different cosmologies. Left: the effect of $\Omega_0$ and $\Lambda_0$ in spatially flat models with a cosmological constant (dark energy equation of state parameter $w = -1$). Right: the effect of changing $w$ for the currently favored cosmology with $\Omega_0 = 0.3$ and $\Lambda_0 = 0.7$.\n
3.3 AGN Physics and Demographics. A large, statistical QSO sample we will generate can be used to address a number of other topical issues:

(a) QSO clustering as a probe of the LSS power spectrum and its evolution out to high $z$’s. This will follow directly the path established by the 2dF Qz survey (e.g., Croom et al. 2001, 2002). The difference is that we would have a much larger sample, but largely with photometric rather than spectroscopic redshifts. Since the sample selection was different, at the very least we should provide an independent check on the 2dF Qz results. QSO clustering can be also used to constrain QSO lifetimes (Martini & Weinberg 2001, Haiman & Hui 2001), and at high $z$’s also the evolution of biasing (see Sec. 3.4).

(b) We will have a database on QSO variability ranging from days to years, and even decades if we fold in the measurements from POSS-I and DPOSS (which we can locally calibrate to our system), and from SDSS where an overlap exists. The mean power spectrum of QSO variability and its possible redshift evolution can be used to constrain both the QSO lifetimes (de Vries et al. 2003, Martini & Schneider 2003) and the power spectrum of accretion, which in turn would provide an empirical constraint for the models of accretion disk instabilities (VandenBerk et al. 2003, and references therein).

(c) We will cross-match our catalogs to 2MASS, FIRST, VLSS, and other surveys and databases ranging from X-rays though radio, as a matter of routine processing, through our NVO interface. This will generate an unprecedented multi-wavelength sample of AGN which can be used to constrain the relative comoving densities of Type 1 and Type 2 AGN as a function of redshift, radio-power, and other factors. This will lead to a better understanding of the AGN demographics over a broad baseline in redshift, which is one of the key projects identified as an early NVO-enabled science.

(d) In the course of this project we will obtain spectra of $>1,000$ QSOs, which can be used to explore a variety of correlations and systematics, such as the Baldwin effect. At a minimum, we should get an independent check on the results obtained by the SDSS, FIRST, and other groups.

3.4 The High-Redshift QSO Survey: Probing the Reionization Era and Early Structure Formation. Exploration of the reionization era, at $z \sim 6 - 20$, is now rapidly becoming the key cosmology frontier. This is when first stars, protogalactic fragments, and first AGN formed, ended the cosmic “dark ages”, and caused the phase transition of the IGM – the reionization (perhaps more than once). While the WMAP data indicate an early start of the reionization (Kogut et al. 2003), QSO spectroscopy indicates the completion of the reionization at $z \sim 6$: Gunn-Peterson-like absorption troughs are now seen along every line of sight to $z > 6$, and there appears to be a steep change in the intensity of the metagalactic ionizing flux at $z \sim 6$ (Fan et al. 2001, Becker et al. 2001, Djorgovski et al. 2001, 2003). While these initial results are exciting, they are not yet conclusive, and much more data are needed before the end of the reionization era is securely established (Fan et al. 2002, Cen & McDonald 2002, Songaila & Cowie 2002, Lidz et al. 2002, Gnedin 2002, etc.). QSOs at $z > 5.5$ are powerful probes of the end of the reionization era, but we are currently limited by the small number of available lines of sight.

Figure 4. An $(r-i)$ vs. $(i-z)$ color-color plot for a small subset of the early-science data, obtained in Sept. 2003. Starlike objects are shown as dots, and several QSO candidates as asterisks. The lines represent the expected QSO color tracks, for 3 different average QSO spectra from the literature; the symbols are spaced by $\Delta z = 0.2$. At $z > 5.6$, the QSO locus intersects the extension of the stellar MS, and IR photometry must be used to separate QSOs from brown dwarfs.
Our goal is to greatly increase the number of known, luminous QSOs at these redshifts, and to use them as probes of the primordial IGM and early LSS and biasing. We would use the BRI color selection to discover QSOs at $z \sim 3.5 - 5.5$, and $riz$ color selection to find objects at $z \sim 5 - 6.5$ (in practice, we will combine the $R$ and $r, I$ and $i$ bands in an optimal fashion). This methodology is now standard, used by DPOSS, SDSS, and other surveys (see Fig. 3). Supplementary $J$-band imaging at several telescopes will be used to separate the $z > 5.5$ QSOs from brown dwarfs. Confirming spectra and redshifts would be obtained at the Palomar 200-inch, and high-S/N, high-resolution spectra needed to study the physics and evolution of the early IGM at the Keck.

This survey will be deeper and more uniform than DPOSS, and reach higher redshifts; it will be comparable to SDSS in terms of the redshift coverage, uniformity, and depth (after 1 year, i.e., 4 passes per field), and will reach twice the depth after 5 years of repeated observations; it will cover a larger area than SDSS, with some overlap (which will provide welcome mutual cross-checks) and also cover new portions of the sky. Down to the depth of SDSS, i.e., within $\sim 1 - 1.5$ years from the start of the project, using the empirical results from DPOSS and the SDSS group (Fan et al. 2001b), over the proposed survey area we expect to discover $\sim 20 - 30$ QSOs at $z \sim 5.5 - 6.5$ (reionization probes), $\sim 100 - 150$ QSOs at $z \sim 4.5 - 5.5$, and $\sim 200 - 400$ QSOs at $z \sim 4 - 4.5$ (primordial LSS probes); some of these QSOs will overlap with the ultimate SDSS QSO sample, but at least a half would be new PQ discoveries. By the time the survey is complete, it will reach twice the depth, and these numbers will roughly double in size.

**Figure 5.** Examples of an $r$-band dropout (top), and an $i$-band dropout (bottom), from the early science data taken in Sept. 2003. The two objects are candidates for QSOs at $z > 4.8$ and $z > 5.6$, respectively.

The formation of the first massive halos, where the first luminous sources will light up, and some of which will contain the first luminous QSOs will be strongly coupled to the primordial LSS, though the standard biasing mechanism, clustering of the highest density peaks (Kaiser 1984; Efstathiou & Rees 1988; etc.). Strong biasing is already detected among the Ly-break galaxies at $z \sim 3$ (Steidel et al. 1998), QSOs and their companions at $z \sim 4 - 5$ (Djorgovski et al. 1999, 2003, and refs. therein), and it should be even stronger at higher redshifts. This is indicated in numerous theoretical studies, e.g., by Brainerd & Villumsen (1994), Matarrese et al. (1997), Moscardini et al. (1998), Blanton et al. (2000), Magliocchetti et al. (2000), Valageas, Silk, & Schaefer (2001), Basilakos & Plionis (2001), etc. The bias factor generally increases with the redshift and the object mass (e.g., especially for the more luminous Lyman-break galaxies or the quasar hosts).

A clumpy distribution of reionization sources would then inevitably lead to an uneven structure of the IGM phase transition. The resulting cosmic variance can be quantified by analyzing the high-S/N, high-resolution spectra of QSOs at $z > 5.5$, e.g., through the autocorrelation of the transmitted flux as an $f(z)$ (Croft et al. 1999, McDonald et al. 2000), the statistics of the opaque windows (Barkana 2002), and the evolution of the ionizing flux (McDonald & Miralda-Escude 2001).

More directly, we can quantify the effects of QSO clustering and its redshift evolution, using our large, statistical sample; coupled with models of structure formation, we can then derive the evolution of
bias for the most massive halos (representatives of which may appear to be an unexpectedly large frequency of $z \sim 4 - 4.5$ QSO pairs and groupings in DPOSS, with comoving separations of $\sim 100 \, h^{-1} \text{Mpc}$ (Fig. 7; Djorgovski 1998, and in prep.), i.e., the physical scale comparable to the 1st CMBR fluctuations peak, and to the characteristic superclustering scales found in some redshift surveys (Broadhurst et al. 1990, Landy et al. 1996). The PQ survey would both increase the statistical sample of QSOs to be used in this test, and provide a check for the possible systematics in the DPOSS data. If the result is confirmed, its implications would be profound: it would represent a primordial LSS, delineated by some of its highest, biased peaks containing quasars, only $\sim 1 \, \text{Gyr}$ after the Big Bang.

**Figure 6.** A cosmic variance in the absorption properties of the IGM around $z \sim 5.5$ (i.e., right after the end of the recombination era), along 4 widely separated lines of sight. (From spectra taken at the Keck telescope, using the ESI instrument; Djorgovski et al., in prep.) This suggests an uneven approach to reionization, possibly caused by the bias-driven clustering of ionizing sources. Many more QSO lines of sight are needed in order to quantify properly this effect.

For example, there appears to be an unexpectedly large frequency of $z \sim 4 - 4.5$ QSO pairs and groupings in DPOSS, with comoving separations of $\sim 100 \, h^{-1} \text{Mpc}$ (Fig. 7; Djorgovski 1998, and in prep.), i.e., the physical scale comparable to the 1st CMBR fluctuations peak, and to the characteristic superclustering scales found in some redshift surveys (Broadhurst et al. 1990, Landy et al. 1996). The PQ survey would both increase the statistical sample of QSOs to be used in this test, and provide a check for the possible systematics in the DPOSS data. If the result is confirmed, its implications would be profound: it would represent a primordial LSS, delineated by some of its highest, biased peaks containing quasars, only $\sim 1 \, \text{Gyr}$ after the Big Bang.

**Figure 7.** Distribution of bright, $z > 4$ QSOs on the northern sky, from wide-field, pre-SDSS surveys. A number of close pairs and groupings are seen, with typical angular separation of $\sim 1 - 2^\circ$ (the expected r.m.s. at this survey depth is $\sim 10^\circ$). The PQ survey can provide a definitive test for this apparent primordial superclustering signal.

Spectra of the high-$z$ QSOs will be also used to constrain the early chemical enrichment in their hosts, and the high end of the SMBH mass function (Dietrich et al. 2003, Warner et al. 2003), both of which may present challenges to theoretical models.

Following our standard practice with the $z > 4$ QSOs discovered in the DPOSS survey (see http://www.astro.caltech.edu/~george/z4.qsos), we would make all of the discovered quasars publicly available on the web as soon as the spectra are taken. This public service would lead to many more scientific returns than what would be accomplished by our group alone.
3.5 Exploration of the Time Domain. The advent of major synoptic sky surveys like PQ is now opening a new discovery domain of parameter space (see, e.g., Paczynski 2000 for a review). While we know about a broad variety of variable sources and phenomena (including AGN, many types of variable stars, SNe, GRBs, etc.), spanning the range of time scales from milliseconds to the Hubble time, the variability of the sky at faint light levels is still largely an unexplored territory, and genuinely new types of objects or phenomena may yet be found. Possible examples include the faint, fast transients found by Tyson et al. (see http://dls.bell-labs.com/transients.html; see Diercks 2001), or megaflares on apparently normal main-sequence stars (Djorgovski et al. 2001).

A key to the timely discovery of transient phenomena, both new and anticipated (e.g., SNe, GRB “orphan afterglows”, OVV QSOs, etc.) is the ability to rapidly recognize the outbursts and follow them up photometrically and spectroscopically. We are designing a real-time data processing pipeline (Fig. 9) to enable such discovery process. The goal is to discover and classify highly-variable sources within minutes of data taking, and to issue automated email alerts for sources deemed sufficiently interesting.

**Figure 8.** An example of an archival DPOSS optical transient. From a pilot project using DPOSS plate overlaps, we estimate that in a single “snapshot”, there will be ~ 10^3 transients/sky down to ~ 19 mag, with the “quiet” states > 21 mag. Many are likely to be high-amplitude variables, SNe, OVV QSOs; a few GRB afterglows; some may be new types of objects.

**Figure 9.** A schematic outline of the real-time discovery pipeline for highly variable sources, to be developed in collaboration with the NSF ITR sponsored project. The system will operate in the real-time, and in addition to the slower, next-day processing pipelines optimized for other tasks, e.g., QSO and lens discovery, galaxies, etc. Key components are interfaces to the external archives using the NVO technology, used to separate asteroids and use multi-wavelength data for a probabilistic classification of detected transients.

In addition to the drift-scan data, we will also use the point-and-shoot exposures obtained by other groups at Caltech and JPL, for the non-Solar-system exploration of the time domain. This will double our data volume, and expand the range of time scales we can probe in the survey.

3.6 Supernovae as a Cosmological Tool. The cosmic acceleration implied by multicolor light curves and spectra of distant SNe Ia (Perlmutter et al. 1999; Riess et al. 1998) has far-reaching ramifications for our understanding of the Universe. Continuing work in this field remains critically important as only SNe
give a direct measure of the expansion history. Our proposed program has two components, both of which take advantage of the synergy established with other telescopes.

(a) Calibrating the absolute luminosity of high-z SNe relies on studies of low-z \( (z \leq 0.1) \) events. For example, uncertainties in world model derived by Perlmutter et al study were affected more by the limited availability of high quality low-z SNe than by the high-z statistics. Several ambitious surveys for high-z SNe are under way with HST and Subaru (and even more ambitious surveys planned with SNAP). The success of each will depend on our ability to calibrate the low-z end of the Hubble diagram, not just in terms of minimizing random errors but also in exploring systematic trends. This is an area where the PQ survey can make a major and lasting contribution by providing a systematic SNe discovery patrol of a large volume at \( z < 0.1 \).

The SN Ia rate is now fairly well known. We expect \( \sim 1 \ z \leq 0.1 \) event per 100 deg\(^2\) per 15 day repeat-observation. In a given lunation we expect to cover up to 3,000 deg\(^2\) yielding on average \( \sim 20 \) – 30 events per month, and over \( \sim 1,000 \) SNe Ia over the proposed lifetime of the survey. With a sample of this size, not only will we have a sound calibration of the low-z end of the SN Ia Hubble diagram, but also a statistically significant sample with which to explore possible environmental effects and other systematics. A key issue for the classification and physical characterization of discovered SNe will be the photometric (light curve) and spectroscopic follow-up. We are in an excellent position to do this, by using the recently-automated Palomar 60-inch and 200-inch telescopes available to the Caltech group, and a 1-m automated telescope at the McDonald Observatory as well as several smaller telescopes at CTIO, available to the Yale group. This work will be considerably expand and be done in conjunction with the LBL-led “Supernova Factory” group with whom a collaborative agreement has been reached. All SN discoveries will be made public promptly, offering the opportunity to the entire community to participate in the follow-up studies and the scientific exploitation of these SN Ia samples.

An important by-product of the search for transient events will be SNe of type II. Traditionally these have not been used as cosmic probes in the manner of SNe Ia because of their heterogeneity and lower mean luminosities. However, for many years it has been proposed that by comparing their bolometric with their expansion velocities, an angular diameter distance can be deduced independently of their light curve properties.

Recently Hamuy & Pinto (2002) have found a remarkably tight correlation between the expansion velocity during the plateau phase for SN IIp with the plateau luminosity, as precise in fact as that based on calibrated luminosity for SNe Ia (0.2 mag, or 9\% in distance). If this relation is borne out by further measures, it will provide a remarkably practical and independent distance indicator to \( z = 0.4 \). For example, 20 – 30 SN IIP located via the ongoing CFHT Legacy Survey and followed up with Keck would verify the cosmic acceleration completely independently of the SN Ia Hubble diagram.

The first step will be to determine the validity of the SN II relation. Events will be selected in the PQ survey using light curves and colors, and followed up spectroscopically at the Palomar 200-inch to measure their redshifts and plateau velocities. We expect to locate 10 SNe II per month on the plateau phase with \( z = 0.05 \). 2 hour integrations on the Palomar 200 inch will be sufficient to establish expansion velocities with the necessary precision.

3.7 Supernovae, GRBs, and the Death of Massive Stars. The PQ survey also offers a unique opportunity to increase our understanding of the cosmic explosions which mark death of massive stars, their physics, and progenitor models for GRBs.

There is now a growing evidence for the association of GRBs and some core-collapse SNe Ib/c. However, while SNe Ib/c are ideal for detecting the signatures of an engine (an accreting compact object as inferred for GRBs), the detailed relation between GRBs and SNe Ib/c remains unclear. This question can be addressed directly using radio observations of local SNe Ib/c (Berger et al. 2002, 2003), which
trace directly the tell-tale signatures of an engine – relativistic ejecta carrying a large fraction of the total energy. To date, only SN1998bw has clearly exhibited these properties (Kulkarni et al. 1998).

At present, the limit on engine-driven SNe Ib/c is about 3% of the total population within 100 Mpc. This statistic is based on VLA radio observations of 33 SNe discovered from late 1999 to the end of 2002 (Berger et al. 2003). However, the predicted fraction of engine-driven SNe Ib/c reaches as low as 0.5%. To assess this fraction directly, using an approved program at the VLA, requires an order of magnitude increase in the number of SNe Ib/c over the next few years. With this increased event rate we may be able to directly probe the relation between GRBs and SNe Ib/c and the properties of the progenitor star and/or explosion processes which determine the fate of a dying massive star.

It is now generally believed that most GRBs are beamed over small solid angles, illuminating roughly 0.5% of the sky with the prompt event (Frail et al. 2001). Most GRBs are thus undetected by high-energy missions, but their optical afterglows would be detectable over a much broader solid angle. Discovery of these off-axis events would provide the first independent confirmation of the collimated-jet model of GRBs, which has been critical to our understanding of GRB energetics. In addition, such “orphan afterglows” would be useful in their own right, as tracers of high-mass star formation and cosmic lighthouses, shining through the gas and dust of their host galaxies.

The multicolor nature of the PQ survey gives us a unique opportunity in the identification of GRB orphan afterglows. Since the synchrotron radiation mechanism of the GRB afterglow produces an emission spectrum very different from stars and quasars, multicolor photometry can be used to identify afterglow candidates in the optical alone (Rhoads 2001).

With the robotization of the Palomar 60-inch telescope and its dedication to transient astronomy, we are equipped to make next-night and, eventually, same-night follow-up observations in multiple filters to recover the transient and confirm its magnitude and colors. If the transient properties are sufficiently interesting then we will trigger follow-up observations with large-aperture telescopes at Palomar and Keck. Optical observations are important for red-shift measurements but it is the radio (VLA) and X-ray (Chandra) that provide the non-thermal (energetics) diagnostics.

3.8 Byproducts and Other Science: From Asteroids and Brown Dwarfs to Large-Scale Structure

The survey will enable a broad range of science which we will not attempt to do by ourselves, simply for the lack of time and manpower on our team. While we will focus our efforts on the studies described above, we will also proactively seek collaborations both within our home institutions, and outside them, for some projects; others will be undoubtedly taken up by the general community as we make our data public. Some of the possible studies include:

(a) **Brown dwarfs and the faint end of the stellar mass function.** Our riz color selection of high-z QSOs is also very effective in picking up late-M and brown dwarfs, which at these magnitudes and moderate and high Galactic latitudes outnumber the QSOs by a factor of 15 or more. We will separate them through IR imaging and P200 spectroscopy, and we will end up with a sample of a few thousand L and T type brown dwarfs. This should lead to a better understanding of their luminosity function and spatial distribution. Prof. Lynne Hillenbrand has expressed some interest in pursuing such a study.

(b) **Variable and HB stars as probes of stellar physics and Galactic structure.** Our variability survey will find many thousands of RR Lyrae, as well as other pulsating variables, whose distances can be deduced from our and subsequent light curve photometry. We should be also able to select photometrically at least some field HB stars and subdwarfs. They can be used to probe the (sub)structure of the Galactic halo, as it was powerfully demonstrated by SDSS and others; see, e.g., Zinn et al. (2003), for an example from Quest-1. Prof. Bob Zinn will be pursuing this type of studies.

(c) **Discovery of asteroids and Kuiper Belt objects.** These will be the principal contaminant of our search for optical transients. We will pass them on to Prof. Mike Brown and the JPL NEAT team, for their own PQ-based studies of such objects.
(d) **A galaxy catalog: galaxian properties and clustering.** We will catalog $> 10^7$ galaxies, including multicolor photometry and morphological parameters. This will be a unique such resource outside the overlap area with SDSS, surpassing the previous photographically based catalogs. The overlap with the 2dF survey is especially interesting: combining their redshifts and our photometry we can reproduce and extend most of the galaxy science done by SDSS, and we can use the overlap area with SDSS to generate a combined galaxy sample for even more powerful statistical studies.

(e) **Automated searches for galaxy clusters and compact groups.** This will be a direct extension of the work we have done with DPOSS (REFS), and comparable to the similar work done by the SDSS. We can generate objective, statistical catalogs of thousands of galaxy clusters in the areas not covered by these surveys, which can be then used for a broad range of follow-up studies. We anticipate collaborations with groups at UC Davis (R. Gal), in Mexico (O. Lopez-Cruz), Italy (G. Longo) and Brazil (R. de Carvalho).

(f) **Automated searches for faint halo globulars, tidal streams, and new dwarf spheroidals.** This would be a direct application of the algorithms used to generate catalogs of clusters of galaxies, but on the stellar catalogs. Color cuts can be used to enhance the contrast for old stellar systems or tidal streams.

(g) **Automated search for low surface brightness (LSB) galaxies.** This will be a direct extension of the work we started with DPOSS, but with the superior CCD data. We anticipate collaboration with groups at UIUC (R. Brunner), U. Oregon (J. Schombert), and in Italy (R. Scaramella).

(h) **NVO cross-matching science.** As a part of our standard processing, we will be cross-matching our object catalogs with both USNO-A and B catalogs, the DPOSS and SDSS catalogs (where an overlap exists), which will provide the proper motions or upper limits for all sources down to the limit of these catalogs. Likewise, we will cross-match with 2MASS, and several radio and X-ray catalogs. These joined data sets can then be used for a broad variety of studies.