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A SEARCH FOR $z \sim 6$ QSOS IN THE PALOMAR-QUEST SKY SURVEY

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RESUMEN

Recientemente, la exploración de las etapas más tempranas de la formación de galaxias y de la estructura, así como del tiempo de la época de la reionización cósmica se encuentran entre las áreas más activas en la investigación cosmológica. En preparación a la operación del GTC y del GTM, estamos haciendo búsquedas de QSOs alrededor de la era de reionización. Estos QSOs serán usados como sondas de la formación de las primeras estructuras masivas en el medio intergaláctico temprano (MIG). Estos objetos masivos son poco frecuentes en cualquier época: por lo tanto es necesario cubrir grandes áreas del cielo para obtener muestras estadísticas. El levantamiento sinóptico del cielo Palomar-Quest (PQ) es una nueva exploración digital de gran envergadura con el telescopio Samuel Oschin de 48-pulgadas en Palomar. La selección de color es una forma eficiente de buscar objetos de alto-z, aunque, para $z \gtrsim 5.5$, las muestras de candidatos a QSO están muy contaminadas por estrellas tardías M y enanas cafés. Sin embargo, por medio de fotometría IR se pueden aislar los candidatos adecuados. El grupo del INAOE está usando el telescopio de 2.1-m del Observatorio Astrofísico Guillermo Haro con la Cámara de infrarrojo cercano para obtener imágenes profundas en la banda J de fuentes puntuales PQ como primeras formas de eliminación i'. Además de las identificaciones de los QSOs de alta-z propuestas, este proyecto identificará un gran número de estrellas de muy baja masa y enanas cafés.

ABSTRACT

Recently, the exploration of the earliest stages of galaxy and structure formation, and the timing of the cosmic reionization epoch have become some of the most active areas in cosmological research. In preparation for the advent of GTC and GTM, we are searching for QSOs around the end of the reionization era. These QSOs will be used as probes for the formation of the first massive structures and the early intergalactic medium (IGM). Such massive objects are rare at any epoch; hence, large areas of the sky have to be covered in order to generate statistical samples. The Palomar-Quest Synoptic Sky Survey (hereafter PQ) is a new major digital sky survey conducted at the Samuel Oschin 48-inch Schmidt telescope at Palomar. Color selection is an efficient way to select high-z objects. However, for $z \gtrsim 5.5$ or so, QSO candidate samples are heavily contaminated by late-M and brown dwarfs. Nevertheless, suitable candidates can be isolated with the aid of IR photometry. The INAOE team is using the 2.1-m Telescope at the Observatorio Astrofísico Guillermo Haro (OAGH) and the Cananea Near-Infrared Camera (CANICA) to obtain deep J-band images of PQ point sources seen as i' drop-outs. Aside from the high-z QSO search proposed above, this project will also generate a large number of very low mass stars and brown dwarfs.

Key Words: **GALAXIES: FORMATION — GALAXIES: HIGH-REDSHIFT — METHODS: OBSERVATIONAL — QUASARS: GENERAL**

1. SCIENTIFIC MOTIVATION

New large sky surveys, and observations with large aperture telescopes and space telescopes are allowing us to explore the epoch of galaxy formation. Although, our current models are still sketchy, those observations are providing us with important clues about the formation of the large-scale structure, the interplay between intergalactic medium (IGM) and the first stars, and the role of AGN on galaxy formation. For a recent review of this subject and further references, see, e.g., Djorgovski (2005).

Following the recombination, about 4×10^5 yrs after the Big Bang, structure grows as dark matter fluctuations collapse and merge, but luminous sources are absent. This period is called the dark

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ages. "Enlightenment" comes about a few hundred million years after the Big Bang when the first stars and AGNs begin to shine and ionize the, then, neutral IGM and, as a consequence, heating it to a temperature about 1.5×10^4 K. During reionization characteristic scales for perturbations growth are modified (Loeb & Barkana 2000). Hence, the dating of this epoch is very important for the understanding of galaxy formation and the enrichment of the IGM.

The first protogalactic starbursts probably appeared at $z \sim 15 - 20$ (see, e.g., reviews by Loeb & Barkana 2000; Barkana & Loeb 2001). The first luminous sources (stars and/or accreting black holes) also caused a phase transition in the IGM, by reionizing it with their UV (and, in the case of the first AGN, soft X-ray) flux. Thus, the first generation of stars, which probably were very massive, hot, and luminous (see, e.g., Bromm et al. 2001; Abel, Bryan, & Norman 2002; Bromm 2004), might have reionized the universe by $z \sim 15 \pm 5$, as indicated by the WMAP measurements (Kogut 2004).

On the other hand, a signature of the reionization's end has been detected in the form of extended opaque regions in the spectra of $z \geq 6$ QSOs (the Gunn-Peterson effect) (e.g., Becker et al. 2001; Djorgovski et al. 2001; Fan et al. 2003). While even small amounts (fraction $\sim 10^{-4}$) of the residual H I can produce the absorption troughs as those observed so far, there does seem to be a qualitative and quantitative change in the opacity of the IGM and the metagalactic UV ionizing flux around $z \sim 6$ (e.g., Fan et al. 2003).

The early history of the IGM, ionizing flux, galaxy and AGN formation was probably very complex, and it is even possible that the universe was reionized twice (e.g., Cen 2003; Wyithe & Loeb 2003; Sokasian et al. 2004). The relative roles played by the first (Population III) and second (Population II) generations of stars, and by the early AGNs (possible "miniquasars", or seed black holes of more luminous QSOs later on), the feedback of the first protogalactic starbursts, the exact nature of the reionization phase transition of the IGM, etc., are all still very poorly understood. We need more observational constraints to probe this fundamental cosmological era.

High-z QSOs in particular are very powerful probes of the processes mentioned above, in several different ways:

First, there is now strong evidence suggesting that massive galaxy formation goes through a QSO phase. There is also indication of co-evolution of QSOs and their hosts; see, e.g., proceedings edited by Ho (2004), or the review by Djorgovski (2005), and references therein. This makes high-z QSOs useful as markers of early sites of massive galaxy formation.

Second, QSOs are the brightest sources we can use to probe the opacity, evolution, and early chemical evolution of the IGM near the end of the reionization era. This information is complementary to that obtained from direct searches for star-forming young galaxies at comparable redshifts.

Third, high-z QSOs may be also excellent tracers of the primordial (highly biased?) large-scale structure (LSS). They were almost certainly associated with massive halos, where the first star formation might have occurred. In the biased galaxy formation scenario, such massive halos should be rare, and may be associated with $\sim 4\sigma$ to 5σ peaks of the primordial density field (e.g., Efstathiou & Rees 1988; Cole & Kaiser 1989; Nusser & Silk 1993). These regions were also the seeds of future rich clusters. This notion is supported by a growing body of observations (e.g., Djorgovski 1999; Djorgovski et al. 2003).

As a corollary, in the generic biased galaxy formation picture, the first luminous sources (galaxies and AGN) must have been strongly clustered due to biasing. Thus, the structure of the IGM phase transition corresponding to the reionization was probably also very clumpy, resulting in *a substantial cosmic variance* among the widely separated lines of sight. Thus, both the evolution of the mean ionizing flux (reflecting the appearance and growth of the first galaxies and AGN) and its spatial variance (reflecting the degree of biasing) are of a considerable cosmological interest.

In order to further our understanding of the processes mentioned above, we need a much larger sample of high-z QSOs than it is currently available. Generating such a sample is one of the key initial science goals of the PQ survey. Observations with the Gran Telescopio Milimétrico (LMT/GTM, http://www.lmtgtm.org/) and Gran Telescopio Canarias (GTC, http://www.iac.es/gabinete/grante/gtc1.html) will play an important role in the exploration of the ionization of IGM, as well as the formation of stars and galaxies at high-z using the PQ-QSOs as probes. In the rest of this paper we describe the PQ survey and some of its scientific goals relevant to this conference.

2. THE PALOMAR-QUEST (PQ) SURVEY

The PQ Digital Synoptic Sky Survey is a collaborative effort between Yale, Caltech, Indiana University and NCSA in the USA, with collaborations with INAOE in México, and other groups, on various specific projects related to the survey. This survey is distinct from the related Palomar-Quest consortium, which is a partnership between Caltech, Yale, and JPL. In this partnership, various hardware components were developed that operate the facility. The data are taken at the historical 48-inch Samuel Oschin Schmidt telescope at Palomar Observatory, using a special 112-CCD camera built for this purpose. Approximately 50% of the time is used for PQ survey drift scans, and the rest is used largely in the traditional point-and-stare mode by groups at JPL and Caltech for exploration of the Solar System. For initial descriptions of the PQ survey, see, e.g., Djorgovski et al. (2004); Graham et al. (2004); Mahabal et al. (2005); Baltay et al. (2005); Djorgovski et al. (2005) and the PQ website (http://www.astro.caltech.edu/pq/).

In the drift scan mode, the PQ survey covers strips $\sim 4.6\,deg$ wide at a constant Dec, with an area coverage of $\sim 500\,deg^2$ per clear night, in 4 filters. The scale is $0.877''/pixel$. The scans are obtained in the range $-25^\circ \leq \delta \leq +25^\circ$, giving the total useful survey area of $\sim 12,000\,deg^2 - 15,000\,deg^2$. The survey uses two sets of filters, the traditional $UBRI$, and the SDSS $r'i'z'z'$, with about equal time share in each. Typical limiting magnitudes in a single pass in good conditions are: $r' \sim 21.5$ mag, $i' \sim 20.5$ mag, $z' \sim 19.5$ mag, $R \sim 22.0$ mag, and $I \sim 21$ mag. With appropriate data coadding, we expect to reach the depths comparable to those reached by SDSS in a year, and twice as deep over the projected survey lifetime.

A significant aspect of the PQ survey is its synoptic nature. We plan to cover all of the survey area with at least 4 passes per year, and some even more often. This will provide time baselines ranging from minutes (one CCD strip to another) to days, to months, and to years, and with matching to SDSS and older Palomar sky surveys, up to several decades. Thus, exploration of the time domain will be a major scientific arena for this survey, which can be considered as a scientific and technical precursor and platform for even more ambitious synoptic sky surveys in the future.

The data rate is about 1 TB per month. Data are reduced and archived at multiple locations (Caltech, NCSA, Yale), with one data pipeline fully operative, and others (e.g., for image combination and for near-real-time detection of optical transients) under development. This will involve a significant use of Grid-based computational technologies.

Another important aspect is that National Virtual Observatory (NVO) standards, protocols, and connections are built in from the start, and will facilitate a very broad data access and analysis.

2.1. *The PQ High-z QSO Survey*

One of the initial scientific goals of the PQ survey is the discovery of a significant number of high-z QSOs, to be used as a statistical sample for studies of early structure formation and reionization. The methodology is similar to that used by SDSS, DPOSS, and other multi-color high-z QSO surveys to date, using colors as discriminant for objects classified as point sources in the images. Using the SDSS depth as the operating level, we note that Fan et al. (2001, 2003) find the surface density of $z \geq 5.5$ QSOs at this flux limit to be $\sim 1/500\,deg^2$. Given the anticipated survey coverage, we expect to find $\sim 15-20$ QSOs at $z \sim 5-5.5$, ~ 50 QSOs at $z \sim 4.5-5$, and ~ 100 QSOs at $z \sim 4-4.5$. Some of our survey area overlaps with that of SDSS, thus providing a valuable cross-check and cross-calibration for both, and some will not be covered by SDSS at all. On the whole, this will be *an unprecedented high-z QSO sample*, useful for a range of cosmological studies. With well-understood completeness limits, it could be used as a new probe of the primordial large-scale clustering and biasing. QSOs at $z \geq 5.5$ are of course essential probes of the end of the reionization era.

The overall survey strategy is as follows: high-z QSO candidates are identified in the PQ data using $BRIr'i'z'$ colors, which in appropriate combinations can be used to find QSOs at $z \sim 4-6.5$ (the high z limit is given by the red cutoff of CCDs). However, whereas QSOs at $z \sim 4-5.5$ can be identified from the optical colors alone, at $z \geq 5.5$ their $(i'-z')$ colors are indistinguishable from those of late-M and brown dwarfs. At the flux levels we probe, and the moderate to high galactic latitudes, and on the basis of the SDSS experience, we expect a contamination of ~ 20 or more late-M and brown dwarfs for each QSO at $z > 5.5$. This contamination can be greatly diminished using IR imaging, as described, in §2.2, below.

After IR photometry, the surviving color-selected candidates are then followed spectroscopically at the Palomar 200-inch telescope. QSOs at $z > 5$ are selected as targets for high-resolution spectroscopy with Keck, and for other follow-up studies. This synergy of telescopes is illustrated in Figure 1.

2.2. *The IR Imaging Component*

We use coadds of 2MASS images to eliminate some of the brighter dwarf contaminants (about

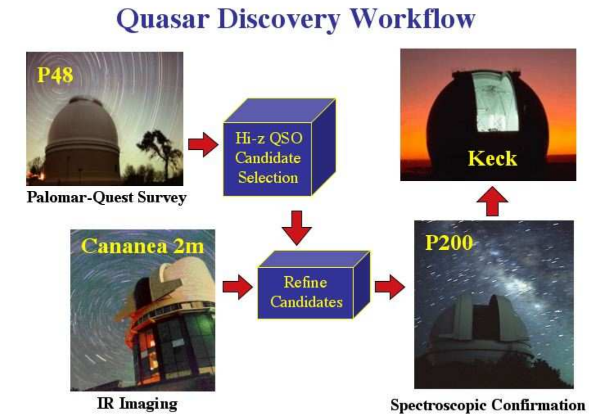

Fig. 1. QSO discovery workflow: QSO candidates are selected from the PQ survey data obtained at the 48-inch Samuel Oshin telescope at Palomar; in order to refine the high-z candidate selection, J band imaging is obtained with the 2.1-m telescope and CANICA at OAGH; spectroscopic confirmation is then done using Palomar 200-inch Hale telescope; and detailed follow-up studies are done at the 10-m Keck telescope and with other major facilities.

a third of the total). However, most candidates require deeper IR imaging. For this aim, we are conducing an intensive observational program to generate deeper IR observations. These observations are carried out with the OAGH 2.1m Telescope (http://www.inaoep.mx/∼astrofi/cananea) using the Cananea Near-Infrared Camera (CANICA, http://www.inaoep.mx/∼astrofi/cananea/canica/). CANICA is based on the 1K x 1K Rockwell Science Center HAWAII (HgCdTe Astronomical Wide Area Infrared Imager) focal plane array. This array has a 76%QE for 99.5% of its area, and a mean dark current is 0.04 e-/sec focal plane array. It includes a cryostat with two 12-position filter wheels and pupil mask. The total field-of-view is $5.5' \times 5.5'$ on the sky, with a scale of $0.32''/pixel$. CANICA is driven by a second generation San Diego State University CCD controller. The array readout and delivery time is 1 second. This project has been awarded 5 nights per month during the past semesters.

The observations are conducted in the shift-and-stare mode (six five minute integrations). Reductions and calibrations are carried out with IRAF using reductions scripts written by D. Thompson at Caltech, and other scripts developed by the CANICA team. For photometric calibrations, standard stars fields from Hunt et al. (1998) are observed nightly. This technique allow us to reach a rms accuracy ~ 0.07 magnitudes in the J-band.

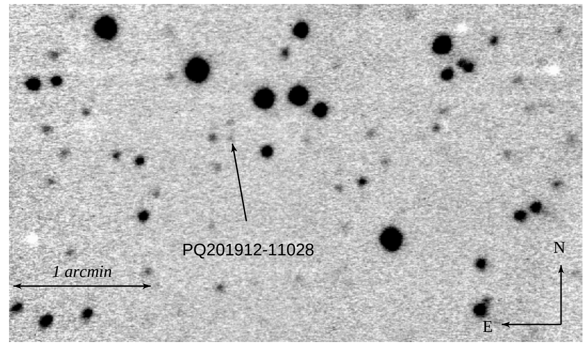

Fig. 2. A $2.6' \times 4.4'$ subsection of the J-band frame of the QSO candidate PQ201912-111028. This a 30 min. exposure (sum of six 5-minute dithered integrations), the magnitude of this object is $J = 18.51 \pm 0.10$. The orientation and the scale are also indicated

In a 30 minutes integration the detection limit is $J \approx 19$ mag. Further checks on our IR photometry are done by comparing with 2MASS point sources that happen to fall with the frames of QSO candidates. In Figure 2 we present the J-band image of QSO-candidate PQ201912-111028, its Vega based magnitude is $J = 18.51 \pm 0.10$. The size of the image is $2.6' \times 4.4'$. The orientation is also indicated.

Our aim is to build a diagnostic diagram similar to Fig. 2 in Fan et al. (2001). This means that in a $(i' - z')\, vs.\, (z' - J)$ diagram, objects whose colors are inside the region delimited by $(i' - z') \gtrsim 2.2$ and $(z' - J) \lesssim 1.5$ are good candidates for $z \sim 6$ QSOs. We have generated a preliminary diagnostic diagram using the z' vs. $(z' - J)$ color-magnitude diagram where only the $(z' - J) \lesssim 1.5$ are considered good candidates for $z \sim 6$ QSOs (see Figure 3). With this scheme we can get rid of more than 60% of the preliminary candidates generated by the PQ survey.

As expected most of the initial PQ candidates are resulting late-M or brown dwarfs. We are taking additional H and K images in order to generate a catalog that will include astrometry, photometric data, and spectral types. This catalog will be available for other studies.

3. OTHER SCIENCE WITH HIGH-Z QSOS

As described in §1, the samples of high-z QSOs can be used as very effective probes of the primordial LSS, the time delimitation of reionization, and the associated cosmic variance. We intend to pursue these studies as the samples are generated, but in addition, there are other exciting possibilities.

Depending on the instrumentation available at GTC, IR spectroscopy will allow us to determine

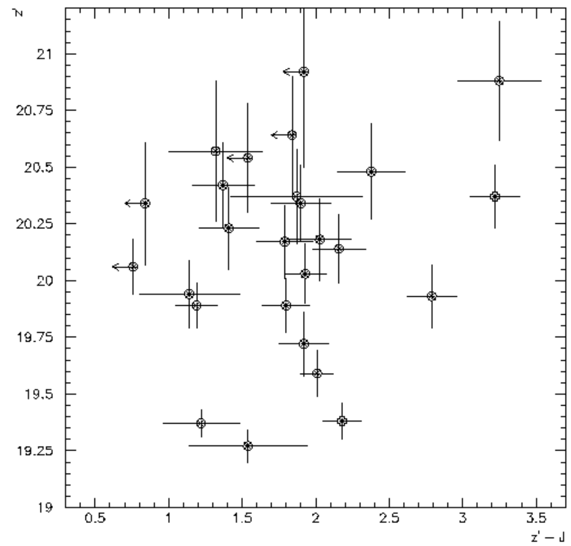

Fig. 3. The z' vs. $(z' - J)$ color-magnitude diagram for high-z QSOs candidates generated by the PQ survey. The J-band (Vega based) photometry was obtained with the OAGH 2.1m telescope and CANICA. $(z' - J) \lesssim 1.5$ are good candidates for $z \sim 6$ QSOs.

QSO metalicities. The same spectroscopic data can be useful to determine the role of dust formation and the enrichment on the ISM (Maiolino et al. 2004). High metalicities (up to $10\times\ Z_{\odot}$!) observed in $z > 4$ quasars (Hamann & Ferland 1993, 1999; Matteucci & Padovani 1993; Dietrich, et al. 2003a) are indicative of rapid chemical evolution, which might be the result of efficient star formation involving several generations of massive stars in a system whose gravitational potential is deep enough to retain and recycle their nucleosynthesis products, e.g., comparable to the cores of giant ellipticals (Romano et al. 2002). Moreover, indications of strong star formation are given by the detections of large amounts of molecular gas and dust in large numbers of high-z QSOs (e.g., Guilloteau et al. 1999; Omont et al. 2001; Bertoldi et al. 2003a,b; Walter et al. 2003). The high-z QSOs discovered within our collaboration will be natural targets for GTM. Observations with the GTM will allow us to determine the molecular gas content and draw constraints on the epoch of star formation in the QSO host galaxies. Some evidence, based on metalicity studies, is already suggesting star formation started at even higher redshifts, perhaps at $z > 10$ (Dietrich, et al. 2003b).

Since these QSOs are also very promising markers of early sites of galaxy formation or even protoclusters (Djorgovski 1999; Djorgovski et al. 2003; Djorgovski 2005), combined observations with GTC (searching for Ly$_{\alpha}$ emitters) and GTM searching for dusty galaxies could open a new game for studies of cluster formation.

4. CONCLUSIONS

In the previous sections we have shown that high-z QSOs play an important role in galaxy and structure formation; and they are also very powerful probes of the reionization epoch. Consequently, we have outlined our strategy for finding those rare high-z QSOs. We have also described some resulting projects for GTC and GTM.

While the PQ survey is just starting, we expect that it will become a major producer of high-z QSOs. IR imaging is crucial to make QSO candidate selection efficient. Hence, the IR follow up program for high$z$ QSO candidates generated by PQ has been proposed as a key project at INAOE. A side product of this effort will be a catalog of late-M and brown dwarfs fainter than the 2MASS flux limit, which would be useful for various follow-up studies on its own.

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