The QUEST–La Silla AGN Variability Survey

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It is widely believed that supermassive black holes reside at the centres of every massive galaxy. When actively accreting they are known as Active Galactic Nuclei (AGNs). Most commonly, their presence is exposed by the radiation generated by the accretion of matter toward their centres. This radiation can show dramatic flux variations on timescales from minutes to years that can be observed across the full electromagnetic spectrum from X-ray to radio wavelengths. Although the exact origin of AGN variability remains unclear, such variability can be used as an efficient tool to find them and to understand the origin and demographics of flux variations. To this end, we have undertaken an AGN variability survey using the QUEST camera on the ESO 1.0-metre Schmidt Telescope at La Silla. The QUEST–La Silla AGN Variability Survey aims to discover thousands of new AGNs, and provide highly sampled light curves to study the ultraviolet/optical flux variations to a limiting magnitude of $r \sim 21.5$ mag.

The long-term variability of active galactic nuclei is mainly the result of modulations in the flux emitted by the accretion disc, although changes in the hot X-ray emitting corona or a possible jet can also drive variations at shorter timescales.

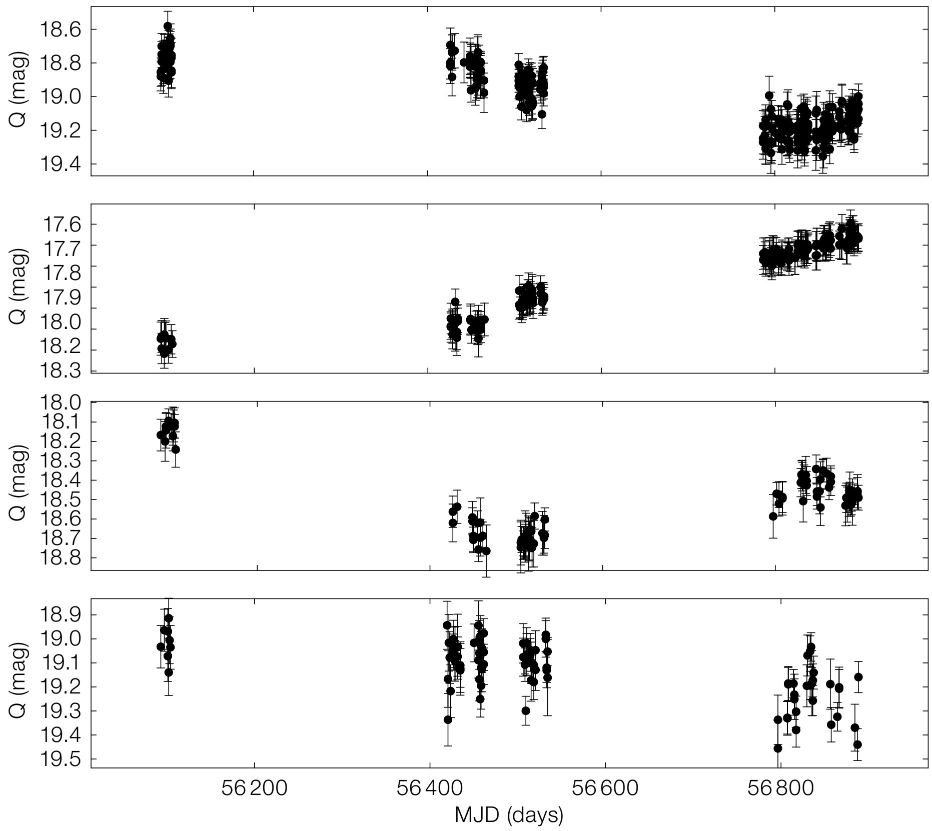

Figure 1. Light curves of QSO candidates in the redshift range $2.5 < z < 3.0$. Selection is based on a combination of colour and variability parameters by our machine-learning algorithm (Cartier et al., 2016). These QSO candidates would be missed by traditional selection methods using colours alone.

Monitoring studies are fundamental to gather information about the extreme physical conditions in the accretion discs near supermassive black holes (SMBHs). The aims of the QUEST–La Silla AGN Variability Survey are: (1) to test and improve variability selection methods for AGNs and to find AGN populations missed by other optical selection techniques; (2) to obtain a large number of well-sampled light curves, covering timescales from days to years; and (3) to study the link between the variability properties (e.g., characteristic timescales and amplitudes of variation) and physical parameters of the systems (e.g., black-hole mass, luminosity, and accretion rate).

Traditionally, optical selection of AGNs has made use of the fact that they show an ultraviolet (UV) excess in their spectral energy distribution when compared to stars (Schmidt & Green, 1983). The UV-excess technique, and more recent selection methods based on optical colours, are very efficient at finding AGNs in regions of colour space where the AGN density is higher than the densities of stars or galaxies. However, such selection methods miss a significant fraction of AGNs with peculiar colours (e.g., red quasi-stellar objects [QSOs]) or AGNs located at a redshift range ($2.5 < z < 3.0$) where their optical colours are similar to those of stars (Fan, 1999). The fact that AGNs are highly variable makes their selection by means of variability a very promising technique to find them, either with or without considering their colours (see some examples in Figure 1). Variability selection has successfully identified a large number of new QSO candidates, and is one of the main goals of the survey.

To expedite follow-up, the QUEST–La Silla AGN Survey monitored sources in several extragalactic survey fields, such as the Cosmological Evolution Survey (COSMOS), Extended Chandra Deep Field South (ECDF-S), ELAIS-S1, the X-ray Multi-Mirror Mission (XMM) Large

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Figure 2. Panoramic view of the La Silla Observatory: the telescopes from background to foreground are: the 3.6-metre, the New Technology Telescope (NTT), the 1-metre ESO Schmidt, the MPG/ESO 2.2-metre, the Danish 1.54-metre, and the MarLy 1-metre.

Scale Structure Survey (LSS) field, and Stripe-82. These regions have extensive and deep multi-wavelength ancillary data from XMM-Newton, Chandra, GALEX, the Hubble Space Telescope (HST), Herschel, Spitzer, and ground-based photometry and spectroscopy, providing valuable constraints on the spectral energy distributions (SEDs), galaxy hosts and environments of the AGN candidates. Additionally, these fields have nearly simultaneous observations in the near-infrared (NIR) performed by the Visible and Infrared Survey Telescope for Astronomy (VISTA) at the Paranal Observatory, which provides information about how the outer and colder portions of the accretion disc and its vicinity vary in relation to the inner parts probed at optical wavelengths.

The telescope and site

To carry out a high cadence variability survey to a limiting magnitude of ~ 21.5 mag, we require a large-format camera that can instantaneously sample a large field of view on a 1-metre or larger telescope at a good observing site. The QUEST2 camera, installed in 2009 on the prime focus of the ESO 1-metre Schmidt telescope at the La Silla Observatory, was the perfect choice. The 160-megapixel array of the QUEST2 camera is well-matched to the large field of view of the ESO Schmidt telescope, which is one of the largest Schmidt configurations in the southern hemisphere (equivalent to the area of 64 full Moons). This unique combination allows an efficient time domain survey to be carried out.

The location of the telescope at the La Silla Observatory is also a perfect complement. La Silla has excellent seeing, a high fraction of clear nights, is very dry and has some of the darkest night skies on Earth (see Figure 2).

In 2009, the ESO Schmidt telescope was fully robotised by the astronomy department of Yale University, and the observations are coordinated by a master scheduling programme (Rabinowitz et al., 2012). At La Silla, the ESO 3.6-metre telescope operator decides when the conditions are appropriate for opening the telescope, and the control software automatically closes the dome whenever the MPG/ESO 2.2-metre telescope is closed, when the Sun rises or when the telescope operator sends a command to close. Since 2011, the telescope has been observing in queue mode for our survey. However, during 2011 and 2012, we had several observing gaps due to problems with the dome wheels of the telescope. The wheels were replaced during 2012, and since 2013 the observations have been taken more regularly.

The QUEST camera and filter response

The camera consists of 112 charge coupled devices (CCDs) arranged in four rows, or fingers, of 28 CCDs each, covering 4.6 by 3.6 degrees (north–south by east–west) on the sky. The fingers are flagged A, B, C and D, and the columns of CCDs from 1 to 28 (see Figure 3 for the layout). Each CCD has 600 × 2400 pixels of 13 × 13 μm and a pixel scale of 0.882 arcseconds per pixel. There are gaps between fingers of 0.43 degrees, such that to obtain a full coverage of the 4.6 × 3.6 degree field of view one must acquire two exposures offset by 0.5 degrees in right ascension (RA). One single pair of exposures is

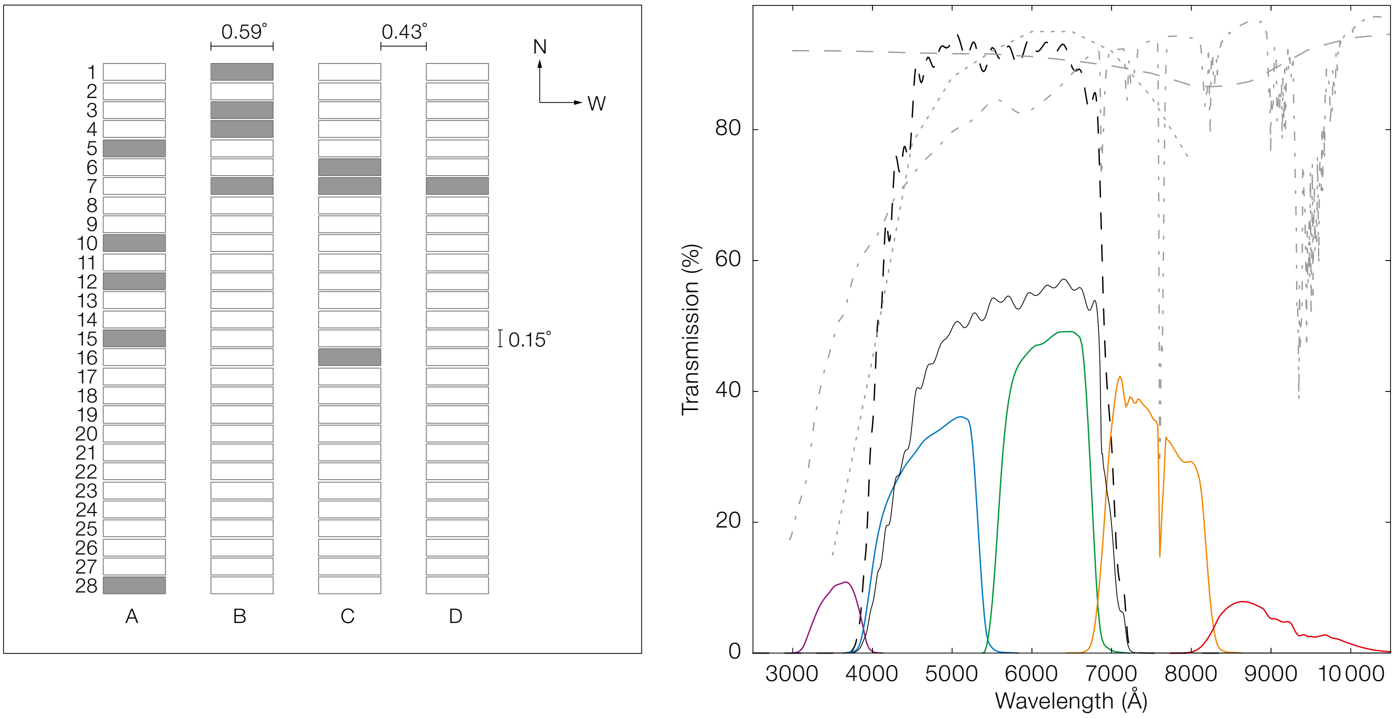

Figure 3. Left-panel: Layout of the QUEST camera array; the camera consists of four fingers of 28 CCDs. The fingers are flagged as A, B, C and D, and the columns from 1 to 28. The gaps between adjacent fingers are 0.43 degrees, and the projected size on the sky of each CCD is 0.59 × 0.15 degrees. In grey we highlight non-functional CCDs. Right-panel: System response of the *Q*-band (solid black) and SDSS bandpasses (in colours) at an airmass of 1.3. We also show the QUEST filter (dashed black; Rabinowitz et al., 2012), the 1-metre ESO Schmidt mirror reflectivity (dashed grey), the sky transmission at an airmass of 1.3 (dot-dashed grey), and the -camera quantum efficiency (dotted grey). From Baltay et al. (2007).

sufficient to cover all of the aforementioned fields, aside from the XMM-LSS field that requires two pairs.

About 16 % of the detector area is non-functional because the CCDs are either permanently off, randomly turn on and off, or have large defective areas, all of which hamper the astrometric solution, owing to the low number of stars detected and the potential for false detections. The effective sky area covered by the functioning CCDs is ~ 7.5 square degrees.

The QUEST–La Silla survey uses a broad *Q*-band filter spanning 4000 to 7000 Å. This bandpass was designed to avoid the fringing often present in the redder images obtained as part of the Palomar-QUEST survey (Baltay et al., 2007). The *Q*-band system response is similar to a broad SDSS ($g + r$) filter (see Figure 3).

Nearly simultaneous near-infrared light curves from VISTA surveys

In addition to the rich multi-wavelength set of data already available, most the survey fields have been observed repeatedly since 2009 in the near-infrared with the 67-megapixel camera (VIRCAM) mounted on the 4-metre wide field VISTA telescope at the Paranal Observatory. The VISTA near-infrared light curves of the COSMOS, ECDF-S, ELAIS-S1, and XMM-LSS fields (see Figure 4) provide nearly simultaneous complementary coverage with the optical data obtained by the QUEST2 camera, and were obtained as part of the UltraVISTA (McCracken et al., 2012) and VISTA Deep Extragalactic Observations (VIDEO; Jarvis et al., 2013) Public Surveys.

Little is known about AGN variability at infrared wavelengths, and our study of VISTA near-infrared light curves is a novel advance in the field (Sanchez et al., 2016). At low redshifts, the near-infrared samples the cooler portions of the accretion disc and the dusty torus that surrounds it. At higher redshifts it provides restframe optical constraints to complement the restframe UV ones obtained by QUEST2. By using both surveys, we expect to have a complete picture of how the emission from the accretion disc is reprocessed by the surrounding dust in obscured AGNs. This can be investigated for AGN with a variety of obscuration levels (i.e., types 1–2), to understand what roles structure, composition and orientation might play.

Status and future of the QUEST2 survey

The QUEST–La Silla AGN variability survey has been collecting data for six years, and the last photometric campaign will be completed by mid-2016. The data reduction process is now robust and well-characterised (i.e., non-linearity correction, photometric system and astrometric solution; see Cartier et al., 2015), and data obtained through 2014 have been reduced for most fields.

Our observing strategy has been to obtain between two to five observations per night to remove spurious variability due to artefacts, to potentially study intra-night AGN variability, and to produce stacked images reaching fainter magnitudes. Individual images reach a limiting magnitude between $r \sim 20.5$ mag and $r \sim 21.5$ mag for an exposure time of 60 or 180 s, respectively.

A reliable variability selection method, based on machine-learning techniques, has been developed (Cartier et al., 2016), and is now being used to find new QSO candidates. During 2015, we began a spectroscopic campaign to classify variable AGN candidates with peculiar colours (likely AGN at $2.5 < z < 3.0$). Our goals here are to: (1) test our selection method; (2) increase our training sample of variable objects with peculiar colours to improve our machine-learning algorithm; and (3) significantly increase the number of known QSOs at this redshift range, in order to obtain a more reliable luminosity function of QSOs at $2.5 < z < 3.0$.

Over the past six years, our project has successfully introduced and trained students in the fields of time-domain astronomy and photometric techniques. Since 2011, four undergraduate students have developed research projects related to the survey and are now pursuing PhDs on topics related to time-domain astronomy. The initial implementation, characterisation and first results of the survey led to the completion of one PhD thesis, while the analysis of the six-year dataset and the spectroscopic follow-up campaign will constitute part of a second thesis under completion.

As part of our survey we have collected light curves not only of AGNs but also of several other interesting transients (see example in Figure 5). Once the survey is completed, we will make our light curves and spectra publicly available to the community.

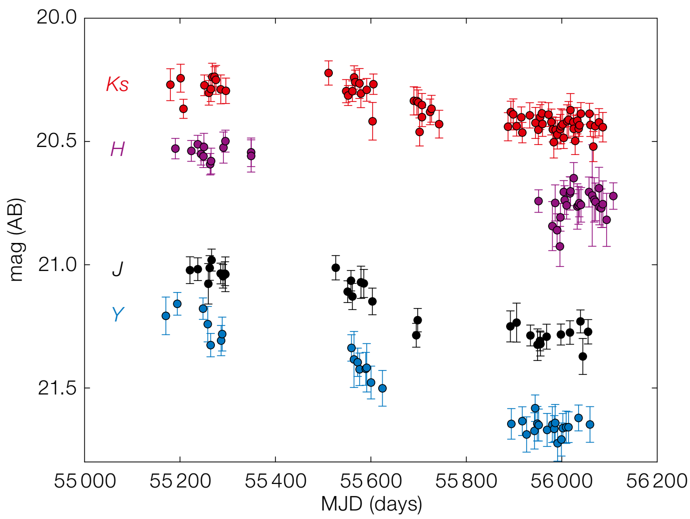

Figure 4. Near-infrared light curve of an AGN obtained by the UltraVISTA survey (McCracken et al., 2012) in one of our fields. NIR light curves for a complete set of AGN in the QUEST–La Silla AGN Variability Survey will be presented in Sanchez et al. (2016).

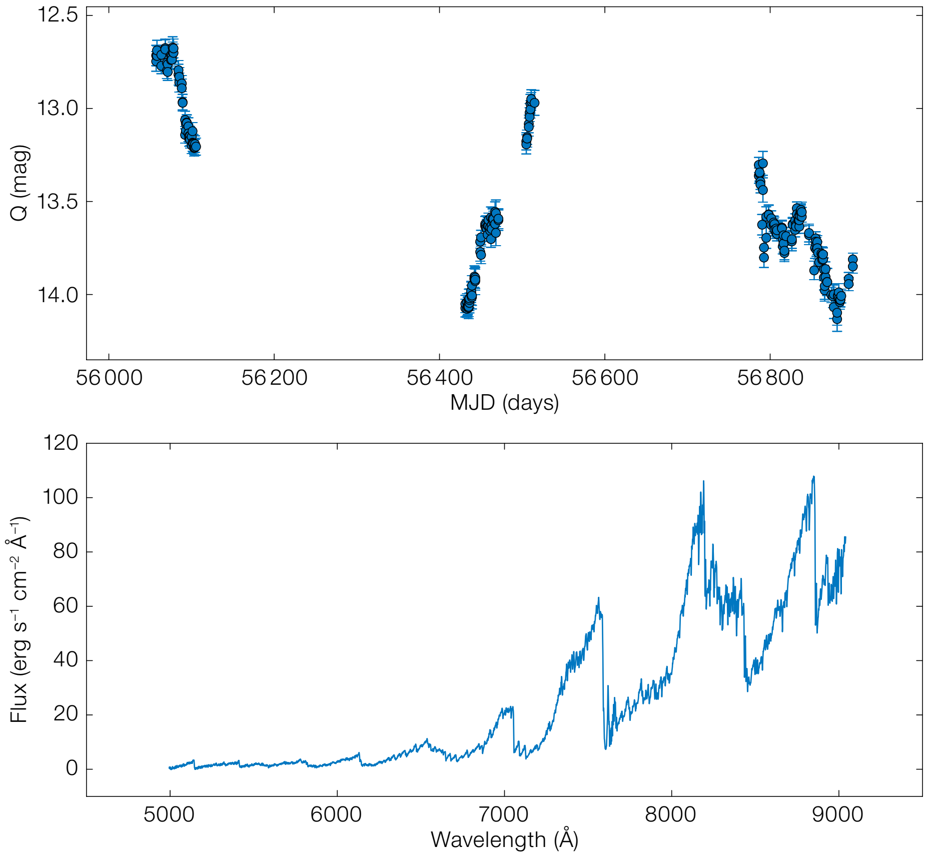

Figure 5. QUEST light curve (upper) and spectrum (lower) of a very red (low temperature) variable star, possibly a Mira star. The spectrum was obtained using the COSMOS instrument on the Blanco 4-metre telescope at Cerro Tololo Inter-American Observatory under poor weather conditions.

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