The La Silla–QUEST Southern Hemisphere Variability Survey

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In 2009, the ESO 1.0-metre Schmidt telescope at La Silla was awakened from an 11-year slumber. The telescope had been decommissioned in 1998 after completing a photographic survey of the southern hemisphere. It has now been given a new life with the installation of Yale University's 160-megapixel QUEST camera consisting of a 112-CCD mosaic covering 10 square degrees. The control system for the telescope was also upgraded to allow fully autonomous observing. With the new system, Yale is conducting the La Silla–QUEST (LSQ) Variability Survey in the Southern Hemisphere to detect low-redshift supernovae, RR Lyrae variable stars, Kuiper Belt Objects (KBOs), and other unusual transients. The LSQ variability survey has already covered most of the southern hemisphere multiple times at cadences ranging from hours to years and to a depth ranging from *R* magnitudes 20.5 to 21.5. To date the survey has detected more than 65 new KBOs and thousands of new RR Lyrae stars. The detection of hundreds of supernovae will lead to an improved measurement of the accelerated expansion rate of the Universe.

The motivation for undertaking the new Schmidt surveys stems from the Yale University's broad interests in understanding Solar System evolution, the structure of the Milky Way and the accelerated expansion of the Universe. A variability survey that repeatedly covers large areas of sky at cadences ranging from hours to days to years serves these goals in several ways. On hourly timescales, the survey exposes the motion of objects in the distant Solar System (Kuiper Belt Objects or KBOs), which are remnant bodies from the time of planet formation. Physical observations of these primitive objects reveal the composition of the early Solar System (Barucci et al., 2008). Also imprinted in the orbital distribution of the KBOs is a record of the early gravitational interactions that scattered planetesimals outward from the inner Solar System (Morbidelli, Levison & Gomes, 2008).

On daily timescales, a variability survey exposes the distinctive brightness oscillations of RR Lyrae stars. These remarkable stars serve as precise distance markers, capable of revealing tidal streams and other large-scale structures in the halo of the Milky Way resulting from past collisions with other galaxies (Vivas et al., 2008). Daily observations also reveal the spectacular outbursts of supernovae in nearby galaxies and other high-luminosity transients (Hadjiyska et al., 2012). These are interesting not only for the extraordinary high-energy phenomena they exhibit, but also because the Type Ia supernovae serve as cosmological distance standards. Measurements of their luminosity versus redshift provided the first evidence of a mysterious dark energy accelerating the expansion of the Universe (Riess et al., 1998; Perlmutter et al., 1999). Future observations of Type Ia supernovae are capable of probing the historical expansion rate of the Universe and thereby constraining the nature of this mysterious force.

The QUEST camera was installed on the ESO Schmidt telescope in 2009 after previously completing a five-year, northern hemisphere variability survey in 2008 using the 1.2-metre Oschin Schmidt telescope at Palomar. At Palomar, this camera was the discovery engine for the Supernova Factory, leading to the measurement of more than 200 spectrophotometric light curves of Type Ia supernovae (Kerschhaggl et al., 2011). It was also used to discover the new dwarf planets in the Kuiper Belt (Brown, 2008; Rabinowitz et al., 2012), to characterise the variability of quasars and to measure the effect of gravitational lensing on quasar variability (Bauer et al., 2012). This article describes the installation of the QUEST camera on the ESO Schmidt and the new surveys being conducted with the instrument.

The telescope upgrade

With the termination of the Palomar KBO and transient surveys in 2008, it was natural to look for an appropriate telescope in the south to complete an all-sky survey for the largest KBOs and to continue the search for supernovae, variable stars and other transients. The ideal telescope would have a Schmidt design, like the Oschin telescope, since the QUEST

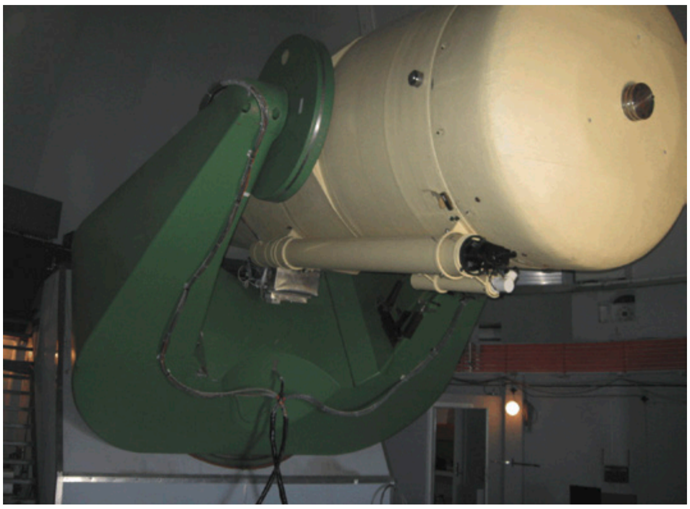

Figure 1. The 1.0-metre ESO Schmidt telescope inside the dome. The QUEST camera is inside the telescope mounted at the prime focus. The camera electronics are visible on the underside of the telescope tube with cabling running up the yoke and around the declination axis.

camera was specifically designed for this configuration. Fortunately, the ESO 1.0-metre Schmidt was available (Figure 1). The telescope is one of the largest Schmidt configurations in the southern hemisphere, situated at an ideal site, and has the same optical configuration as the Palomar Schmidt (but smaller entrance aperture). The QUEST camera could be installed without any changes to its front-end optics. ESO provided Yale with the opportunity to use this telescope with the expectation that Yale would update the control system for automated operation, replace the plate holder at the prime focus with the 160-megapixel QUEST camera, and establish an independent internet connection for transfer of the image data to Yale. Yale began to implement these changes in early 2009, and was ready for remote and automated operation of the ESO Schmidt by August 2009.

Since the original control system for the ESO Schmidt was over 30 years old and no longer usable, the entire system had to be upgraded. This required a complete replacement of the control electronics for both telescope axes and the focus mechanism, including servo amplifiers, encoders, the controlling computer and control software. With the new system it is possible to run the telescope in a fully robotic mode with no one at the telescope. In typical operation, observing scripts are prepared at Yale during the day and transmitted to a computer at the telescope. At night a master scheduling program automatically sequences telescope pointing, dome rotation, focus sequences and camera exposures. This automation is essential for running the survey every clear night of the year. The operator of the ESO 3.6-metre telescope, sitting in the main control room at La Silla, can monitor and control the opening and closing of the Schmidt dome via a web interface to ensure that it is closed in case of inclement weather.

Because LSQ must process each night of survey data at Yale the day after acquisition, they require a communication link to La Silla that can handle ~ 50 Gbytes per night (after compression). Unfortunately, no such link was available at La Silla. Yale therefore installed a private, high-speed radio link between La Silla and Cerro Tololo, where there is direct 100-kilometre line of sight (Figure 2). Programmable radios connected to 2-metre-diameter antennas were installed with experimental software developed for long-distance links in developing countries. The radio link achieves a bit rate of ~ 20 Mbits/sec, sufficient to transmit the survey data to Yale as fast as they are acquired. The receiving antenna at Cerro Tololo connects to a high-speed internet backbone that is linked to the US mainland.

Figure 2. Installation of a 2-metre-diameter radio antenna on the La Silla weather tower. A matching antenna at Cerro Tololo receives the LSQ image data and transmits them to Yale over a high-speed internet link with the USA.

The QUEST camera

The 160-megapixel QUEST camera (Figure 3) was designed and fabricated at Yale University in collaboration with a group from Indiana University for initial operation at the Oschin Schmidt telescope at Palomar (Baltay et al., 2007). It was installed on the ESO Schmidt without any changes to the CCD array or the camera dewar. The focal plane consists of 112 CCDs fabricated by Sarnoff Labs. Each is a thinned, back-illuminated device with 600 × 2400 13 μm pixels with a peak quantum efficiency of 95 % at 600 nm. The array covers 3.6 × 4.6 degrees, with an active area of 9.6 degrees^2 and a pixel scale of 0.87 arcseconds.

The focal plane is cooled with a pair of 60 Watt cryo-refrigerators. Each unit transfers heat using a Gifford–McMahon cycle, where compressed helium at room temperature drives the motion of a piston, thereby drawing thermal energy from the cold head at the end of the piston

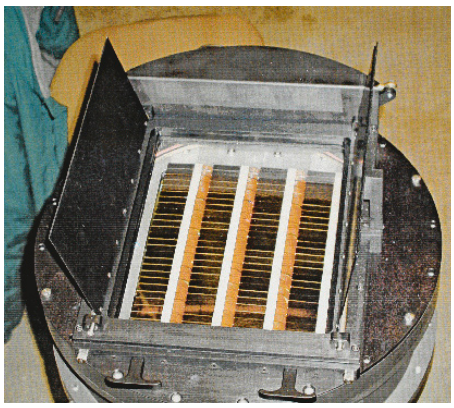

Figure 3. The 10-square-degree QUEST camera. The focal plane of the 161-megapixel camera consists of 112 CCD devices arranged in four rows with 28 CCDs each. The array spans 3.6 × 4.6 degrees with an active area of 9.6 square degrees.

cylinder. Two large helium compressors sit on the dome floor beneath the telescope, connected by long, flexible high-pressure lines to the piston heads. Recirculated water cools each compressor, with the heat dissipated outside the dome by air/water heat exchangers. To minimise vibration of the focal plane induced by the piston cycling, the two cryo-refrigerators are firmly bolted to the stiff spider vanes supporting the focus hub of the telescope. Because the units mechanically connect to the camera head only by flexible copper straps and flexible vacuum housings, their vibrational energy is almost completely absorbed by the large mass of the telescope. There is no detectable influence from the vibration on image quality.

For all current surveys LSQ uses a single wideband filter covering the 400 to 700 nm range. The red cutoff eliminates fringing in the images due to strong atmospheric emission lines at red wavelengths. The blue cutoff reduces the background from moonlight. Other filter sets are available, including a single plate of Schott glass RG610, and sets that combine four different filters (Johnson *U,B,R,I* or Gunn *g,r,i,z*), each covering a different row of CCDs in the array.

System performance

In the first three years of operation the telescope and camera have performed well given that all exposures are unguided and unmonitored during the night. Typical seeing is 1.6 arcseconds for 60 s exposures and 2.0 arcseconds for 180 s exposures. Pointing repeatability is ~ 10 arcseconds night-to-night. Photometric precision is ~ 1.5 % for field stars observed repeatedly over many nights. The only serious instrumental problem was a failure of the support wheels for the dome owing to the aging of rubber components. This has now been fixed by a complete replacement of the old wheels with new bogies designed by G. Ihle.

The search for KBOs

In recent years, surveys for KBOs conducted with the QUEST camera have exposed a new population of dwarf planets with sizes close to that of Pluto, ultimately leading to the new definition of a planet that excluded Pluto from the list of major planets. Earlier surveys covering much smaller areas to fainter limits had already detected hundreds of fainter KBOs and established that Pluto follows a typical Kuiper Belt orbit. But the much larger size and brightness of Pluto relative to its dynamical cousins had preserved its place among the planetary pantheon. Only with the discovery at Palomar of other bodies like Pluto, massive enough to gravitationally retain a surface rich in volatile ices, did it become clear that Pluto was not unique. But of more importance to our understanding of the origin and evolution of the Solar System, the discovery of the dwarf planets has led to a new understanding of KBO composition and structure, volatile retention, collisional dynamics, surface weathering and dynamical evolution.

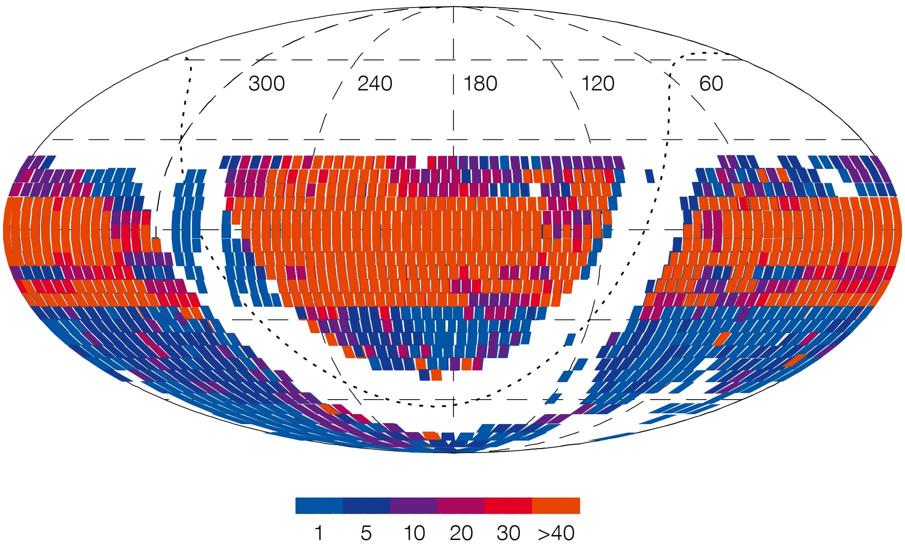

Figure 4. Survey areas covered to date by La Silla–QUEST survey are shown. The colour codes the number of visits per field. Blue areas have been covered at least three times per night for the KBO survey; red areas have been covered extensively for the supernova and RR Lyrae surveys in addition to the KBO survey.

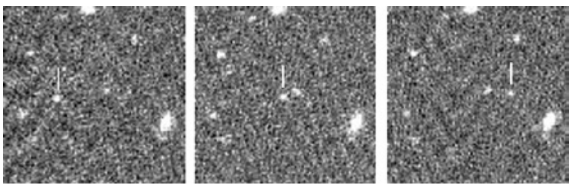

Figure 5. The discovery images of the distant KBO 2010 WG9 with magnitude *R* ~ 20.5. In each square panel north is up, east to the left, the image size is 88 by 88 arcseconds and the position of the source is indicated by a white line. The time interval is ~ 2 hours between exposures.

The LSQ survey further explores the population of large KBOs. It is intended to cover the entire sky south of the ecliptic to magnitude limit *R* ~ 21.5, including areas not accessible to, or not completely searched by, previous northern hemisphere searches. To date, no other KBO surveys of comparable scale and sensitivity have been conducted in the south. Based on the discovery rate of large KBOs at Palomar and their wide-ranging latitudes, at least a few similar-sized KBOs likely remain undiscovered in the south.

The sky coverage of the KBO survey is shown in Figure 4. Each survey area has been covered at least three times per night for the KBO search. More than 65 new KBOs have been detected, including redetections of the dwarf planets Eris and Sedna. However, no new objects larger than ~ 500 kilometres have yet been discovered. One of the most interesting new objects is 2010 WG9, a distant body with an inclination exceeding 70 degrees and a perihelion near the orbit of Uranus. The discovery images are shown in Figure 5. Only two other bodies are known with similarly high inclinations and distant perihelia. As with long-period comets, commonly observed when they pass into the inner Solar System, 2010 WG9 is likely a returning member of the Oort Cloud. However, it has somehow managed to follow an unusual path allowing Uranus or Neptune to capture the orbit and prevent a closer passage. As such, it may be one of the few observed bodies from the Oort Cloud unaltered by a close passage to the Sun. Observations to determine its physical properties are in progress.

The Supernova Survey

Type Ia supernovae have recently received much attention as calibratable standard candles in cosmological studies, particularly for the role they play in the discovery of the acceleration of the expansion of our Universe. In order to carry these studies to an increased level of precision, a number of surveys have gathered samples of relatively high redshift supernovae. Additional high redshift surveys are being planned, including the Large Synoptic Survey Telescope (LSST) and the space mission WFIRST. As the detections at high redshift become numerous, there is new scientific motivation to carry out a large-scale survey for low-redshift supernovae. In particular, the low-redshift sample anchors the Hubble Diagram at the most recent epoch of expansion. Measurements of the nearby supernovae are necessary to reduce the error obtained on the resulting cosmological parameters. Also, detailed physical studies of the low-redshift supernovae improve our understanding of their ensemble properties and their use as distance indicators.

In order to detect supernova, the LSQ survey covers a given set of fields repeatedly, usually with a two-day cadence (set A is covered on the first night, set B on the second, repeat set A on the third, repeat set B on the fourth, and so on). Similar to other surveys, LSQ uses a rolling search, repeating observations of most of the fields in these two sets for several months. Once a particular field has been observed multiple times in good conditions, a reference image of the field can be made. Subsequent observations of the field can then be sent through the LSQ subtraction pipeline, which subtracts the reference image from each new image and detects transients by identifying the residual sources in the subtracted images.

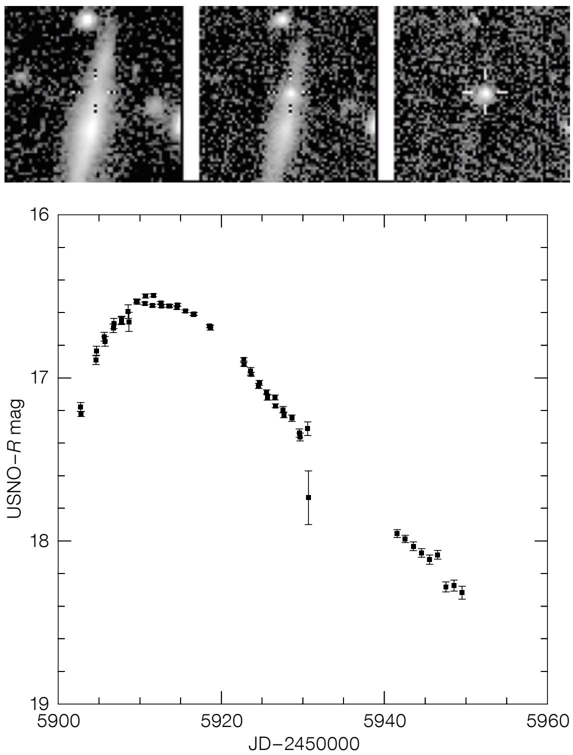

Figure 6. Discovery subimages for the Type Ia supernova LSQ11ot, redshift 0.026, showing the reference, new and subtracted images (left to right, upper panel). The subimages are each 0.94 by 0.94 arcminutes. The host-subtracted light curve for the Type Ia supernova LSQ11bk, redshift 0.03, is shown (lower panel).

On a given night, typically ~ 1000 potential transients are detected and must be visually scanned to remove noise artefacts. Of the remaining candidates, those that appear near or on top of galaxies and have historical variability inconsistent with variable stars are scheduled for spectroscopic follow-up. Figure 6 shows LSQ discovery images for one Type Ia supernova and a light curve of a second one, both discovered at low redshift.

The area covered to date by the supernova survey is shown in Figure 4 (red areas). The search has been concentrated between −25 and +25 degrees declination to allow follow-up by both northern and southern observers. Most of this area has been covered in excess of 40 times in the last three years. Several hundred supernovae have been discovered. More than 100 have been followed up and confirmed spectroscopically by collaborators, including the Public ESO Spectroscopic Survey of Transient Objects (PESSTO) which uses the EFOSC spectrometer on the ESO New Technology Telescope (NTT), located just a few hundred metres from the ESO Schmidt.

The study of RR Lyrae variables

The properties of the halo of our galaxy and how they may be explained in the broader context of galaxy evolution has been an active area of research for many years. Early models assumed a smooth uniform distribution of stars in a halo formed during the early stage of collapse of our galaxy. Recent studies however suggest that accretion of satellite galaxies has played a major role in the formation of the Halo, leaving significant structure inside the Halo. RR Lyrae are periodic variable stars with uniform intrinsic luminosities, hence they make excellent standard candles for probing the structure of the Galactic Halo. LSQ has been used to gather a large sample of RR Lyrae stars, providing sensitivity to remnants of galaxy mergers in the Halo. In a search of 1300 square degrees, a total of about 2000 RR Lyrae variables were found with magnitudes between 14.5 and 20.5, corresponding to distances from 6 to 100 kiloparsecs. Figure 7 shows a few representative light curves.

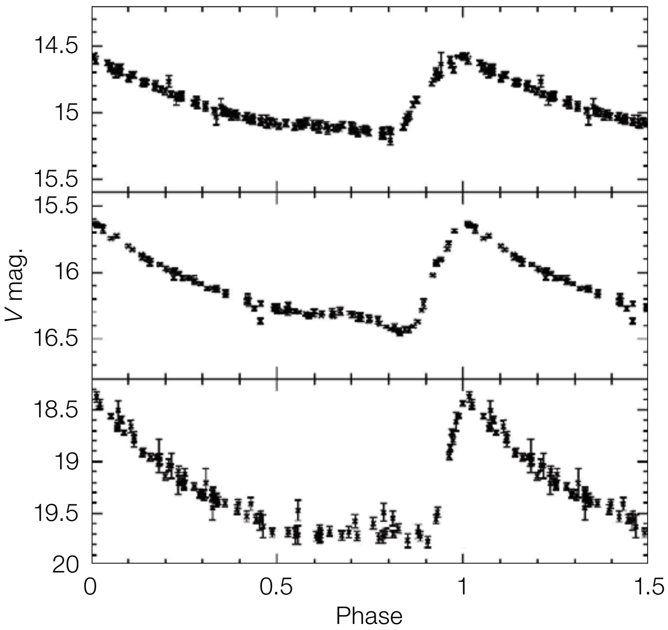

Figure 7. LSQ light curve measurements of a few typical RR Lyrae variable stars. The observations are phased by the light-curve period and photometrically calibrated using Sloan Digital Sky Survey field stars.

Future plans

In collaboration with other institutions in the United States and PESSTO, Yale University plans to continue the LSQ supernova survey for several more years. A new survey for high-inclination KBOs is also planned, with the search area concentrated near the ecliptic pole and pushed to fainter magnitudes in order to find more unusual bodies, like 2010 WG9. The cooperative working relationship between Yale University and ESO staff at La Silla has been extremely fruitful, leading to a revitalised observing programme with the ESO Schmidt. The collaboration promises to yield many exciting discoveries in the years to come, spanning the range from planetismals to exploding stars.

Acknowledgements

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References

Baltay, C. et al. 2007, PASP, 119, 1278
Barucci, M. et al. 2008, in *The Solar System Beyond Neptune*, ed. M. Barruci, H. et al., Univ. Arizona Press, 275
Bauer, A. et al. 2012, ApJ, 749, 56
Brown, M. 2008, in *The Solar System Beyond Neptune*, ed. M. Barruci et al., Univ. Arizona Press, 335
Hadjiyska, E. et al. 2012, Proc. IAU, 285, 324
Kerschhaggl, M. et al. 2011, PrPNP, 66, 335
Morbidelli, A., Levison, H. & Gomes, R. 2008, in *The Solar System Beyond Neptune*, ed. M. Barruci, et al., Univ. Arizona Press, 275
Perlmutter, S. et al. 1999, ApJ, 517, 565
Rabinowitz, D. et al. 2012, AJ, 144, 140
Riess, A. et al. 1998, AJ, 116, 1009
Vivas, A. et al. 2008, AJ, 136, 1645

A photograph of the 1-metre Schmidt telescope on La Silla taken in 1971 during its first test period is shown. Otto Heckmann, the first ESO Director General, is standing in front of the telescope.