Towards a Fundamental Astrometric Reference System behind the Magellanic Clouds: Spectroscopic Confirmation of New Quasar Candidates Selected in the Near-infrared

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Quasi-stellar objects (quasars) located behind nearby galaxies provide an excellent absolute reference system for astrometric studies, but they are difficult to identify because of fore- and background contamination. We have embarked on a programme to expand the quasar reference system behind the Large and Small Magellanic Clouds, the Magellanic Bridge and Magellanic Stream. Hundreds of quasar candidates were selected, based on their near-infrared colours and variability properties from the ESO VISTA Magellanic Clouds (VMC) Public Survey. A subset of 49 objects was followed up with optical spectroscopy with FORS2. We confirmed the quasar nature of 37 objects (34 new identifications) that span a redshift range from z ~ 0.5 to 4.1.

Quasi-stellar objects (quasars) are active nuclei of distant galaxies, undergoing episodes of strong accretion. Typically, the contribution from the host galaxy is small, and they appear as point-like objects with strong emission lines. Quasars are cosmological probes that serve as background "beacons" to explore the intervening interstellar medium, but they also are distant, unmoving objects used to establish an absolute astrometric reference system on the sky. The smaller the measured proper motions (PMs) of foreground objects are, the more useful the quasars become — as is the case for nearby galaxies. Quasars behind these galaxies are hard to identify because of foreground contamination, the additional (patchy) reddening inside the intervening galaxies themselves, and the galaxies' relatively large angular areas on the sky. The latter point underscores the need to carry out dedicated wide-field surveys, sometimes covering hundreds of square degrees, to find a sufficient density of background quasars. The Magellanic Clouds are an extreme case where these obstacles are notably enhanced.

The VISTA survey of the Magellanic Clouds

The ESO Public Survey with the VLT Infrared Survey Telescope for Astronomy (VISTA) of the Magellanic Clouds (VMC; Cioni et al., 2011) covers 184 square degrees around the Large and Small Magellanic Clouds (LMC, SMC), the Magellanic Bridge, and the Stream (Figure 1). The magnitude limit is to Ks = 20.3 mag (signal-to-noise ratio ~ 10; Vega system) in the $YJKs$-bands; 12 separate epochs in the Ks-band, spread over at least a year are also taken. The main survey goals are to study the star formation history and the geometry of the Magellanic Cloud system, as well as its cluster and variable-star populations.

The VMC is carried out with VISTA (Emerson et al., 2006), a 4.1-metre telescope on Cerro Paranal, equipped with the VISTA InfraRed CAMera (VIRCAM; Dalton et al., 2006), a wide-field near-infrared camera producing ~ 1 by 1.5 degree images across the 0.9–2.4 μm wavelength range. The VISTA data are processed with the VISTA Data Flow System (VDFS) pipeline (Irwin et al., 2004) at the Cambridge Astronomical Survey Unit[1]. The data products are available through the ESO Science Archive[2] or the specialised VISTA Science Archive (VSA; Cross et al., 2012).

Quasar candidate selection

Cioni et al. (2013) derived selection criteria (Figure 2) to identify candidate quasars based on both the locus of 117 known quasars in a (Y–J) versus (J–Ks) colour–colour diagram and their Ks-band variability behaviour. The diagram was based on average magnitudes obtained from deep tile images created by the Wide Field Astronomy Unit (WFAU[3]) as part of the VMC data processing, using version 1.3.0 of the VDFS pipeline.

Figure 2 shows the colour–colour diagram demonstrating the colour selection of our quasar candidates. The regions (marked with letters) where known quasars are found and the locus of the planetary nebulae (Cioni et al., 2013) is indicated. The blue crosses (×) indicate VMC counterparts to the spectroscopically confirmed quasars (Cioni et al., 2013), selected adopting a maximum matching radius of 1 arcsecond (the average separation is 0.15 ± 0.26 arcseconds).

The selected candidates for our study are included in Ivanov et al. (2016); for the quantitative description of the selection criteria, see Cioni et al. (2013). Extended sources were included in our search to ensure that low-redshift quasars with considerable contributions from their host galaxies were not omitted. Their extended nature is marginal, because they are dominated by their nuclei, and they are still useful for quasar absorption-line studies. The 68 brightest candidates were selected to homogeneously sample seven VMC tiles where quasars had not yet been found. The total number of

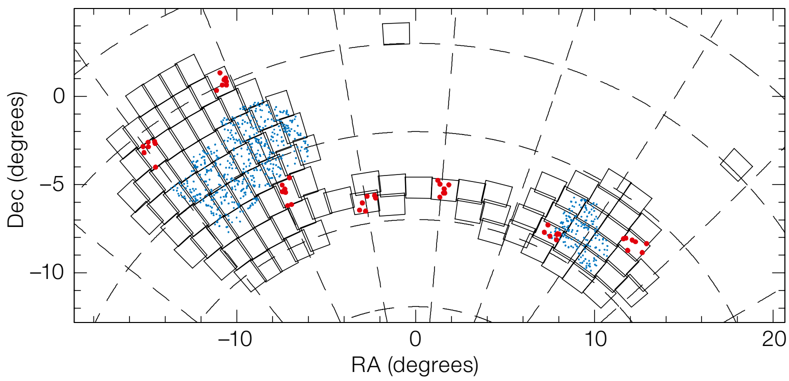

Figure 1. VMC footprints on the sky (shown as contiguous rectangles). The spectroscopically followed-up quasar candidates are marked in red, and confirmed quasars from Kozlowski et al. (2013) in blue. The dashed grid shows lines of constant right ascension (spaced by 15°), and constant declination (spaced by 5°). Coordinates are given with respect to (RA, Dec) = (51°, −69°).

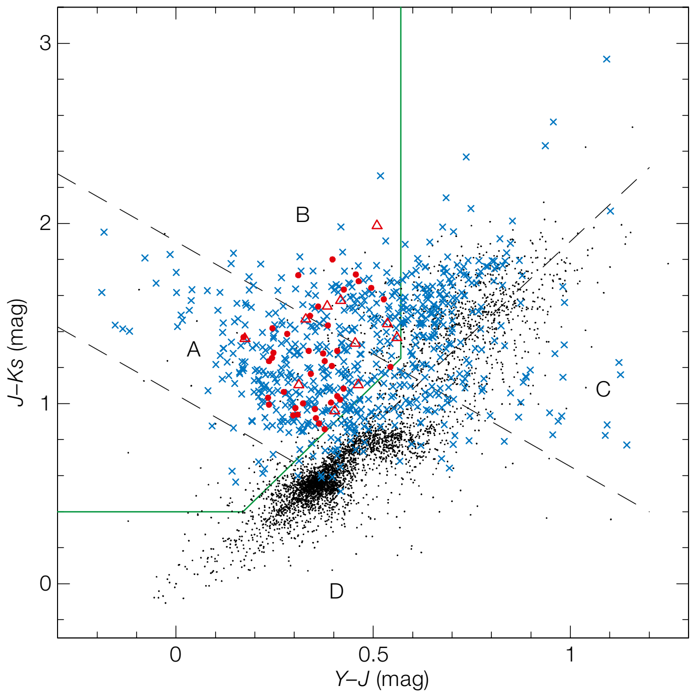

Figure 2. Colour–colour diagram showing the colour selection of our quasar candidates. The dashed black lines identify the regions (marked with letters) where known quasars are found, while the green line marks the blue border of the planetary nebulae locus. The spectroscopically followed-up quasars are marked with solid red dots, while the non-quasars are marked with red triangles. Blue crosses (×) indicate the location of the VMC counterparts to the spectroscopically confirmed quasars from Kozłowski et al. (2013). Black dots are randomly selected LMC objects (with errors in all three bands of < 0.1 mag), to demonstrate the locus of "normal" stars, as well as background galaxies in regions B and C.

candidates could increase greatly if fainter objects are considered.

Spectroscopic follow-up observations

Follow-up spectra of 49 candidates were obtained with the FOcal Reducer and low-dispersion Spectrograph (FORS2; Appenzeller et al., 1998) on the Very Large Telescope in long-slit mode, with the 300V+10 grism, delivering spectra over λ = 445–865 nm with a spectral resolving power R ~ 440 (1.3-arcsecond slit). Two 450 s exposures were taken for most objects, except for some fainter objects, for which the exposure times were 900 s. The signal-to-noise ratio (S/N) varies among the spectra, but it is typically ~ 10–30 at λ ~ 6000–6200 Å. The observing details are given in Ivanov et al. (2016). The data reduction was carried out using the ESO pipeline, version 5.0.0. Various IRAF[4] tasks from the onedspec and rv packages were used in the subsequent analysis. Some reduced spectra are shown in Figure 3.

Prominent emission lines were identified, from which the quasar redshifts were measured. For most line centres the typical formal statistical errors are $\Delta\lambda$ ~1 Å, which translates into redshift errors $\Delta z < 0.001$. These are optimistic estimates that neglect wavelength calibration errors. We evaluated the latter by measuring the wavelengths of 45 strong and isolated sky lines in five randomly selected spectra. We did not find any trends with wavelength and a root mean square (rms) error of 1.57 Å was determined. This translates into a redshift uncertainty of Δz ~ 0.0002 for a line at 7000 Å, near the centre of our spectral coverage. To evaluate the real uncertainties, we compared the redshifts derived from different lines of the same object. The average difference for 35 pairs of lines, for quasars with multiple lines, is effectively zero: $|z_i – z_j| = 0.006 \pm 0.007$.

For objects with multiple lines we adopted the average difference as redshift error, adding in quadrature the wavelength calibration error of $\Delta z = 0.0002$. This addition only made a difference for a few low-redshift objects. For quasars for which only a single line was available, we conservatively adopted as redshift errors $\Delta z = 0.005$ for objects at $z < 1$ and $\Delta z = 0.015$ for more distant objects. Finally, as external verification, in the Sloan Digital Sky Survey (SDSS) rest frame composite spectrum we re-measured the redshifts of the same lines that were detected in our spectra, obtaining values below $z = 0.0001$, as expected.

Results

The majority of the observed objects are quasars: 37 objects appear to be *bona fide* quasars at z ~ 0.47–4.10 (10 are located behind the LMC, 13 behind the SMC and 14 behind the Bridge area), showing some broad emission lines, even though some spectra need smoothing for display purposes. The spectra of the three highest-redshift quasars exhibit Lyα absorption systems; a few quasars (e.g., SMC 3_5 22, BRI 2_8 197, etc.) show blue-shifted C IV absorption, perhaps due to winds from active galactic nuclei. We defer a more detailed study of individual objects until the remainder of the sample have been followed up. Our success rate is ~76 %, testifying to the robustness and reliability of our selection

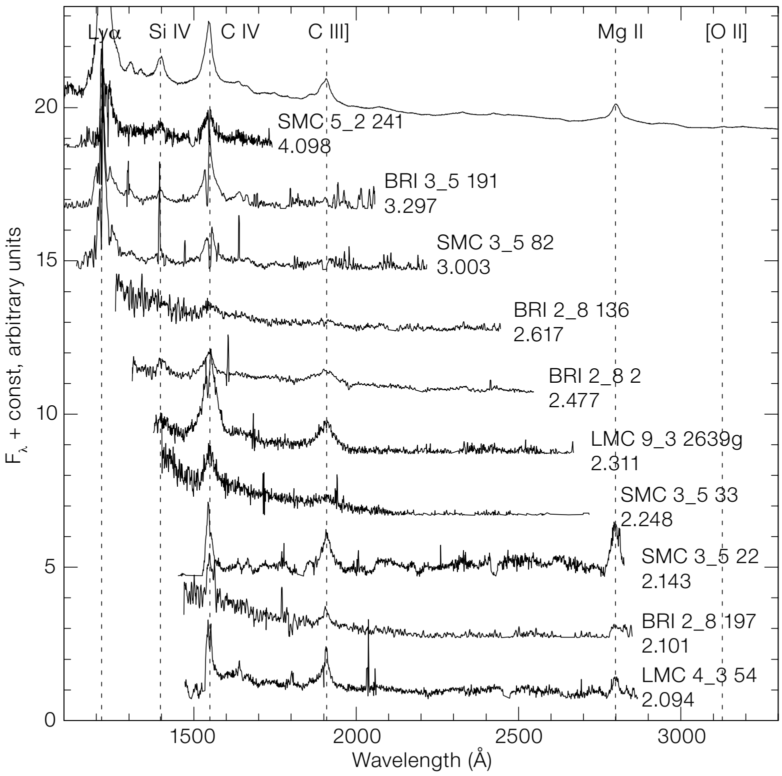

Figure 3. Example spectra of the quasar candidates sorted by redshift, shifted to restframe wavelength. The spectra were normalised to an average value of 1.0, and shifted vertically by offsets of two, four, etc., for display purposes. The SDSS composite quasar spectrum (Vanden Berk et al., 2001) is shown at the top.

criteria. Many of our quasars are present in the GALEX and SAGE–SMC (Surveying the Agents of Galaxy Evolution – Small Magellanic Cloud) source catalogues. The confirmed quasar SMC 5_2 241 has a candidate radio counterpart: SUMSS J002956–714640 at 2.8 arcseconds separation, detected in the 843 MHz Sydney University Molonglo Sky Survey.

Many quasars with redshifts $z \leq 1$ were classified as extended sources by the VDFS pipeline, supporting our decision to include extended objects in the sample: they are either contaminated by the host galaxy or by chance alignment with foreground objects from either the LMC or the SMC. Four extended objects are contaminating low-redshift galaxies: LMC 9_3 2728g, LMC 8_8 655g, and LMC 8_8 208g show hydrogen, some oxygen and nitrogen in emission, but no obvious broad lines, so we interpret these as indicators of ongoing star formation rather than nuclear activity; while LMC 8_8 341g may also show Hβ in absorption. In addition, LMC 8_8 341g has a recession velocity of ~ 300 km s^{-1}, consistent within the uncertainties with LMC membership, making it a possible, moderately young LMC star cluster. After target selection we realised that three of our candidates (SMC 5_2 203, SMC 3_5 24, and SMC 3_5 15) were previously confirmed quasars, and two others (LMC 9_3 137 and LMC 4_3 95g) were previously suspected quasars.

Three point-source-like objects are most likely emission-line stars: LMC 4_3 95, LMC 4_3 86, and SMC 3_5 29. The spectra of LMC 8_8 422g, LMC 4_3 3314g, and LMC 9_3 3107g do not offer any solid clues as to their nature. Some BL Lacertae (BL Lacs) — active galaxies believed to be seen along a relativistic jet emanating from the active nucleus — are also featureless, but they usually have bluer continua than the spectra of these three objects. A possible test is to search for rapid variability, typical of BL Lacs, but the VMC cadence is not well-suited for such an exercise, and the light curves of the three objects do not show any peculiarities. Finally, the spectra of LMC 4_3 1029g and LMC 8_8 376g are too noisy for secure classification.

Prospects

Cioni et al. (2013) estimated that the VMC survey may find a total of approximately 1830 quasars. The success rate of 76 % reached here brings this number down to some 1390. The spectra of the candidates in seven tiles, of the 110 tiles that make up the entire VMC survey, yielded on average ~ 5.3 quasars per tile. Scaling this number up to the full survey area yields ~ 580 quasars. This is a lower limit, because only the brightest candidates in the seven tiles were followed up, so the larger number is still a viable prediction.

This project is still at an early stage, but once spectroscopic confirmations have been achieved, the identified quasars will provide an excellent, independent reference system for detailed astrometric studies of the Magellanic Clouds system, complementing Gaia. In addition, the homogeneous, multi-epoch observations of the VMC survey, combined with the large quasar sample, open up the possibility to investigate in detail the mechanisms that drive quasar variability, for example, with structure functions in the near-infrared, following the example of the SDSS quasar variability studies.

References

Appenzeller, I. et al. 1998, The Messenger, 94, 1
Cioni, M.-R. L. et al. 2011, A&A, 527, 116
Cioni, M.-R. L. et al. 2013, A&A, 549, A29
Cross, N. J. G. et al. 2012, A&A, 548, 119
Dalton, G. B. et al. 2006, SPIE Conf. Ser., 6269, 30
Emerson, J. et al. 2006, The Messenger, 126, 41
Ivanov, V. et al. 2016, A&A, in press, arXiv:1510.05504
Irwin, M. J. et al. 2004, SPIE Conf. Ser., 5493, 411
Kozlowski, S. et al. 2013, ApJ, 775, 92
Vanden Berk, D. E. et al. 2001, AJ, 122, 549

Links

1 Cambridge Astronomical Survey Unit (CASU): http://casu.ast.cam.ac.uk/
2 ESO Science Archive: http://archive.eso.org
3 Wide Field Astronomy Unit (WFAU): http://www.roe.ac.uk/ifa/wfau/
4 The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), under a cooperative agreement with the US National Science Foundation.