A&A 438, 949–955 (2005)
DOI: 10.1051/0004-6361:20042274

Astronomy & Astrophysics

A search for very active stars in the Galaxy*

First results

G. Tsarevsky[1,2,3], José A. de Freitas Pacheco[4], N. Kardashev[2], P. de Laverny[4], F. Thévenin[4], O. B. Slee[1], R. A. Stathakis[5], E. Barsukova[6], V. Goransky[7], and B. Komberg[2]

1 Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 1710, Australia
e-mail: gregory.tsarevsky@atnf.csiro.au
2 Astro Space Center, Lebedev Physical Institute, 84/32 Profsoyuznaya St., 117997 Moscow, Russia
3 Isaac Newton Institute of Chile, Moscow Branch, 13 Universitetskij Pr., Moscow 119992, Russia
4 Observatoire de la Côte d'Azur, BP 4229, 06304 Nice Cedex 4, France
e-mail: thevenin@obs-nice.fr
5 Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia
6 Special Astrophysical Observatory, Nizhnij Arkhyz, Karachaevo-Cherkesia 369167, Russia
7 Sternberg Astronomical Institute, 13 Universitetskij Pr., Moscow 119992, Russia

Received 28 October 2004 / Accepted 9 February 2005

Abstract. We report the first results of a systematic search near the plane of the Galaxy for so-called very active stars (VAS), which are characterized by a hard X-ray spectrum and activity in the radio domain. Candidates with hard X-ray binary-like spectra have been selected from the Bright ROSAT Source Catalogue in the Zone of Avoidance ($|b| < 20°$) and were tentatively identified in GB6/PMM/NVSS radio surveys. Most of them were observed with the ATCA and VLA. Precise radio coordinates have led to unambiguous optical identification for 60 candidates, and a sub-sample of five of them has been observed with the VLT. Also some discovery and confirmatory spectra were obtained with the AAT (4-m) and BTA (6-m). Spectroscopy with moderate dispersion, made with the FORS1 spectrograph of the VLT has revealed two stellar objects (one of them, VASC J1628-41, is definitively a binary VAS), one new AGN and two featureless spectrum sources. One of these objects, VASC J1353-66, shows marginal evidence of proper motion, which, if confirmed, would imply the discovery of a new type of galactic source.

Key words. stars: activity

1. Introduction

We report the first results of a search for very active stars (VAS) in the Galaxy, defined as "ordinary" active stars, i.e., stars detected as bright X-ray emitters, having a hard X-ray spectrum and activity in the radio domain. These aspects are detailed below and compared with other similar active objects.

Active stars (AS) are members of a wide class presenting variability in different spectral domains with prominent emission in X-ray and, in many cases, in radio. Included in this category are eruptive variables (e.g., Orion and UV Ceti type stars); cataclysmic (or explosive) variables (CV) (e.g., different types of novae and nova-like stars); RS CVn type and X-ray binaries (XRB) (including microquasars, MCQ). The latter sub-class, MCQ, will be given special attention in this paper.

An important key to understand the nature of AS is their distribution in the "two-colour" X-ray diagram, HR1 – HR2. These quantities are the hardness ratios resulting from the combination of X-ray fluxes in four bands covering the range 0.1–2.0 keV of the ROSAT PSPC instrument (Voges et al. 1999). Such a plot was exploited by Motch et al. (1998, see their Fig. 2), which clearly shows that XRBs (unlike "ordinary" active stars, CV or AGNs) have a prominently strong concentration in a narrow strip in the extreme upper right corner of the HR1 – HR2 plane. Motch et al. (1998) claimed that such a concentration could not be produced by selective X-ray absorption in the disk of the Galaxy. Therefore, an extreme hardness ratio is a real and intrinsic property of XRB (and MCQ).

According to Mirabel & Rodríguez (1999), microquasars are XRBs displaying highly accelerated radio jets. Thus we

* Based on data collected at ESO/VLT Paranal (Chile) Program ID 71.D-0176(A), Australia Telescope Compact Array (CSIRO), Very Large Array (NRAO, USA), Anglo-Australian Observatory and Special Astrophysical Observatory (Russia).

can search for new VAS, including MCQ, using X-ray hardness and radio detection as basic criteria for selection. In contrast, "ordinary" AS are preferentially soft (and even ultrasoft) X-ray emitters, and not all of them are well-detected radio emitters. Hereafter, we refer to VAS objects having: a) a hard X-ray spectrum (in terms of the ROSAT energy range, 0.1−2 keV); and b) a detectable radio emission. To date, approximately 50 objects among the ∼300 known XRBs (Liu et al. 2001) have already been detected at radio wavelengths (Wendker 1995; Fender & Hendry 2000; McCormick 2003), but only ∼16 of them have a radio emission morphology typical of MCQs. Thus, the present number of known microquasars is still too small to perform meaningful statistical studies in order to answer questions concerning their nature, evolution and other phenomena. In spite of the small number of well-classified MCQs, some major (though obviously quite controversial) characteristics can be mentioned: a) a black hole (BH) or a neutron star (NS) as a primary; b) a high mass (HM) or a low mass (LM) secondary; c) transient or persistent emission at different wavelengths; and d) in some cases are associated with X-ray novae. These characteristics indicate that MCQs constitute a very heterogeneous family, stimulating researchers to detect new objects of this class. In particular, Paredes et al. (2002) surveyed the plane of the Galaxy in the latitude range $|b| < 5°$ in the area covered by the NRAO VLA Sky Survey (NVSS), which is restricted to declinations $\delta > -40°$, i.e., about a quarter of the Milky Way was not covered. They did not find any new MCQ and came to the conclusion that the number of MCQ in the Galaxy is probably very small (Marti et al. 2004). Our data seem to confirm such a conclusion.

We have extended this search to $|b| < 20°$ along the whole Zone of Avoidance (ZOA), aiming to find new very active stars, including MCQs, in the Galaxy.

It is interesting to note that those sources from the Bright ROSAT Source Catalogue (1RXS release) by Voges et al. (1999) having $HR1 \geq 0.90$ and $HR2 \geq 0.25$ (i.e., those falling onto the "XRB strip") show a remarkable concentration towards the galactic plane and the galactic centre. This sample of 759 objects (526 are within our selection area) consists of different types of active sources, and contains an unknown proportion of extragalactic objects. Thus this concentration could be influenced, at least partially, by selective HI absorption of the X-ray emission. Nevertheless, it probably indicates that some fraction of the sources traces a genuine Galactic population of VAS.

In the present paper we report spectroscopic observations of a sample of five VAS candidates, performed with the VLT at ESO (Paranal), supplemented by observations made with the Anglo-Australian Telescope (AAT) and the 6-m Russian Telescope (BTA). The radio data were obtained with the Australia Telescope Compact Array (CA) and the Very Large Array (VLA). These observations are part of a complete survey conducted in both hemispheres using the selection criteria described in Sect. 2. In Sect. 3 observations and data reduction are described, and in Sect. 4 we analyze the objects individually. In Sect. 5 we present our concluding remarks.

2. The sample: selection criteria

The idea and corresponding strategy to find new VAS are as follows (Tsarevsky et al. 2002, 2003)[1]:

Step 1: selection of low galactic latitude sources ($|b| < 20°$) from the ROSAT All-Sky Survey Bright Source Catalogue, 1RXS release (Voges et al. 1999) by the following criteria specific to XRB:

$$0.90 \leq HR1 \leq 1.00, \quad \text{and} \quad 0.25 \leq HR2 \leq 1.00.$$

It is possible that this selection criterion missed some of the VAS, if they were temporarily in a soft state at the time of the ROSAT observations. However, we expect the number of missing objects to be relatively small. Indeed, for XRBs, Fig. 2 of Motch et al. (1998) shows that most of them are in a hard state, which could be explained by Comptonization in the corona around the accretion disk. We have also discarded sources with position errors of more than 15″ and an extension parameter more than 100″. Thus, we have selected an initial sample of 428 sources for further study.

Step 2: in line with the VAS definition (see above), we found tentative radio identifications for the sources of Step 1 in the following surveys: GB6 and 87GB (4.8 GHz, Gregory et al. 1996)[2], PMN (4.8 GHz, Griffiths et al. 1994) and NVSS (1.4 GHz, Condon et al. 1998). An upper limit of the ROSAT to radio coordinate uncertainty was chosen as 1.0 arcmin for the 87GB/GB6/PMN, and 0.6 arcmin for NVSS catalogues. This way we tentatively identified in radio wavelength 201 of 428 ROSAT sources.

Step 3: further high-sensitivity and sub-arcsec resolution radio observations with the CA and VLA, to obtain accurate coordinates for unambiguous optical identifications, and to find their radio morphology and possible variability. We have already observed 85 of 201 sources, and five of them are briefly discussed in this paper.

Step 4: optical identifications on DSS plates, which, due to the precision of the CA/VLA coordinates, are in most cases unambiguous (i.e., the radio-optical coordinate difference, $|r - o|$, is less than 1.5″, see examples in Table 2), even in overcrowded fields along the Milky Way. For some sources still not observed by the CA/VLA, we have also used NVSS data, especially for those brighter targets with more precise coordinates (28 in our case). Such NVSS-only based identifications are not unambiguous and need confirmation by high resolution CA/VLA observations.

At this stage of the survey, we have discarded galaxies clearly recognized in the DSS. Note that most of these are new radio galaxies behind the Milky-Way,

[1] The survey algorithm described below is similar to that developed by Paredes et al. (2002).

[2] It is useful to use the GB6 and 87GB catalogues together, to check for radio variability which is expected to be for sources like VAS.

Table 1. Log of the VLT, AAT and BTA observations and X-ray hardness (HR1, HR2) of the targets.

VASC name	Name 1RXS	l deg.	b deg.	Epoch	Telescope	Resolution ($km\,s^{-1}$)	λ-coverage (Å)	$HR1$	$HR2$
$J1353-66$	J135341.1–664002	309.1	–4.5	10-May-03	AAT	120	4350−7350	0.93	0.56
				01/02-Aug.-03	VLT	200	4855−6960		
$J1626-33$	J162620.7–332925	346.1	10.8	25/26/31-Jul.-03	VLT	200	4855−6960	1.00	0.65
$J1628-41$	J162848.1–415241	340.3	4.7	02-Apr.-01	AAT	170	4000−7400	1.00	0.60
				31-Jul./02-Aug.-03	VLT	200	4855−6960		
$J1757-41$	J175715.6–414914	350.0	–8.5	31-Jul.-03	VLT	200	4855−6960	1.00	0.61
$J1942+10$	J194246.3+103339	48.3	–6.4	17-Jun.-02	BTA	820	5630−8050	1.00	0.67
				18/23/25-Sep.-03	VLT	200	4855−6960		

i.e., in the ZOA – a valuable by-product of this investigation. In this way, 53 galaxies have been discarded from further consideration in the context of this project. Therefore, only 60 star-like objects were retained for subsequent spectroscopic observations.

Step 5: moderate resolution spectroscopic observations of the optically identified star-like VAS candidates (VASC). We have already made such observations for 50 VASC along the whole ZOA using the following telescopes: AAT (4-m, AAO, Australia), BTA (6-m, SAO, Russia) and VLT UT2 (8-m, ESO, Chile).

After this step, some objects clearly showed their AGN (QSO/Sy) nature (e.g., object VASC J1757-41 in our current sub-sample, see Sect. 4), and therefore they constitute another by-product of the survey. Excluding extragalactic objects, the remainder are stars (e.g., VASC J1626-33 and VASC J1628-41, see Sect. 4) believed to be potential VAS candidates.

3. Observations and data reduction

3.1. Radio observations

Following step 3 of our selection algorithm (Sect. 2), we have observed our VAS candidates using the CA (at 4.8 and 8.6 GHz in a 6-km configuration during 2000−2003) for the objects south of Dec = −30°, and the VLA (at 4.8 GHz in A-configuration on 18 Oct. of 2000) for the only object in the current sub-sample north of −30°, VASC J1942+10.

The data were routinely processed with the AIPS and MIRIAD packages. Four of the five sources have not been resolved by the sub-arcsec resolution of the CA/VLA, so we do not show their radio maps here. One source, J1757-41, a half-Jy object and a newly discovered Seyfert (see Table 2 and Sect. 4.4), shows arcsec radio structure and a definitely unresolved core. Thus precise radio coordinates were measured for these five sources, permitting their unambiguous optical identification. Table 2 contains the resulting radio parameters.

More details of the observations and data reduction will be given in a separate paper, together with radio data of all 85 sources observed.

3.2. Optical identifications

Thanks to the unambiguous optical identifications mentioned above, there is no need to show finding charts for four of five sources considered in this paper. Indeed, they can easily be found via a conventional on-line DSS facility (e.g., USNO B1.0 Catalogue) – see Table 2 for corresponding coordinates and magnitudes.

However, source VASC J1626-33 has a close companion – an anonymous galaxy barely resolved in the DSS plates. Thus, we adjusted the slit orientation to obtain simultaneous spectra of both objects. An excellent VLT map of this complex, reconstructed from the FORS1 image record, is shown in Fig. 4 (see Sect. 4.2 for more details).

3.3. Optical spectroscopy

The spectra of five VAS candidates were obtained with FORS1 (Focal Reducer low dispersion Spectrograph) attached to the 8-m KUEYEN (UT2) telescope, during the period June-September 2003. The GRISM 600V was used, allowing a wavelength coverage ranging from Hβ to Hα with a spectral resolution of 200 km s^{-1} *FWHM*. The slit width was uniformly set to 1″. The orientation of the slit for each target was chosen in order to include one or two sources close to the center of the radio identification and to check possible misidentifications in some crowded areas. Integration times up to 45 min were scheduled to achieve the desired $S/N = 50$. The data were reduced using standard procedures of the MIDAS package. We performed sky background subtraction to eliminate undesirable emission lines and carried out a wavelength calibration using He, Hg/Cd and Ar spectra. Pixels with a deviation greater than 5σ from the expected intensity profile were ignored. This allowed us to eliminate the majority of cosmic rays and CCD defects.

We have also used spectra obtained with the AAT in service mode (4-m; RGO spectrograph, 120 to 300 km s^{-1} resolution, typical slit width 1.5″) and BTA (6-m; UAGS spectrograph, 820 km s^{-1} resolution, typical slit width 2″). Details are given in Table 1.

Data were reduced using standard routines, similarly to VLT spectra.

Table 2. Results of radio and optical observations.

VASC name	CA/VLA Coordinates (4.8 GHz) RA 2000	Dec 2000	NVSS F1.4 mJy	CA/VLA F4.8 mJy	CA F8.6 mJy	Sp. Ind. α	USNO $\|r-o\|$ $''$	USNO R mag	Spectral classification
$J1353-66$	13 53 40.15	−66 39 57.58	–	48.2 ± 0.1	41.7 ± 0.1	−0.2	0.5	17.1	Featureless
$J1626-33$	16 26 23.08	−33 29 33.62	21.8±0.8	0.7 ± 0.1	0.8 ± 0.1	+0.2:	0.7	15.1	Star K0 III
$J1628-41$	16 28 47.285	−41 52 39.14	–	8.8 ± 0.1	12.3 ± 0.1	+0.7	0.7	12.4	Star K3 III-IV
$J1757-41$	17 57 15.658	−41 49 18.76	–	488.5 ± 0.2	398.9 ± 0.2	−0.3	0.3	17.0	Sy1, z = 0.3342
$J1942+10$	19 42 47.484	+10 33 27.11	99.0 ± 0.5	106.0 ± 0.2	–	+0.1:	0.2	16.1	Featureless

4. Results

The results from inspection of our spectra, as well as other related optical and radio data, are summarized in Table 2. Columns 4−5 give radio coordinates obtained at 4.8 GHz with the CA or VLA (for the VASC J1942+10 only). The subsequent four columns contain a brief summary of radio data: flux densities at 1.4 GHz (taken from NVSS), 4.8 GHz (CA or VLA), 8.6 GHz (CA) and a spectral index α (in the sense $F_\nu \propto \nu^\alpha$). Column 8 shows radio to optical identification quality as a corresponding position difference, $|r-o|$. Column 9 the gives R-magnitude taken from the USNO B1.0 Catalogue. The last column gives a brief spectrum description detailed in the following subsections.

4.1. VASC J1353-66

The VLT data show a featureless spectrum with the interstellar (IS) NaI doublet and some weak diffuse interstellar bands (DIB) at 5770 Å and 6280 Å (Fig. 1). The AAT spectrum, obtained on 10 May 2003, confirms the featureless spectrum of the object. Taking into account the detected X-ray and radio emission, this source is probably a new BL Lac type object behind the Galaxy. Its position in the sky is in the vicinity of the Great Attractor (Woudt & Kraan-Korteweg 2001). However, the Naval Observatory Merged Astrometry Dataset (NOMAD Catalogue) gives a small proper motion for this object (μ(RA) = 20 ± 5, μ(Dec) = −4 ± 6 mas/y). Despite being significant at the 4σ level, is a marginal result since only three low-quality Schmidt-DSS plates were measured. If confirmed, it would suggest the discovery of a new type of galactic source (see discussion in Sect. 5). The resonant doublet Na I$\lambda\lambda$5890-96 is quite well detected and barely resolved in our VLT spectra, with an intensity ratio between components near unity (see Fig. 1) and an estimated equivalent width of $EW(D_1 + D_2)$ = 2.96 Å. The Na I doublet is primarily an indicator of the interstellar reddening (Munari & Zwitter 1997) but it can be used to give a rough distance estimate (Allen 1973). Since the line is saturated, only a lower limit of 3 kpc can be derived from the statistical relation between distance and EW(NaI). Even so, this lower limit implies a rather high transverse velocity ~300 km s^{-1}, which cannot presently be excluded for such a peculiar object.

4.2. VASC J1626-33

There are two barely resolved objects on the DSS plates: a star at the radio position (see Table 2) and a galaxy in 3.5$''$ PA = 45° from the star. The slit was conveniently orientated in order to include both objects.

SW component: the VLT spectrum indicates that this object is a K0-1 III star, classified according to comparison with a template set and using the intensity ratio Hα/(CaI+BaI+FeI), with a radial velocity of +24 ± 2 km s^{-1}.

This object is a potential VAS candidate. Figure 2 shows the VLT spectrum, including the identification of the main spectral lines.

The NVSS catalogue gives at this position a 21.8 mJy source at 1.4 GHz, which contradicts CA detection below 1 mJy at 4.8 and 8.6 GHz on 3 Jun. 2000, suggesting a possible strong radio variability (see Table 2).

NE component: this object was identified as an elliptical galaxy at $z = 0.1092 \pm 0.0002$. The classification and estimated redshift are consistent with the identification of absorption features such as the G-band, Hβ, the MgI-blend and the NaI doublet. Using the FORS1 imaging ability, we have constructed a high quality R-image of the field shown in Fig. 4. Inspection of this image indicates a morphology typical of an early-type galaxy (E0), confirming the interpretation resulting from the analysis of its spectrum (Fig. 3). Coordinates and magnitude were derived from the image shown in Fig. 4 as RA = 16h26m23.2s, Dec = −33°29$^{\rm m}$32.1$''$ (J2000) and R = 17.0 m.

Both sources possibly have infrared (2MASS) counterparts, 16262293-3329342 and 16262316-3329319, respectively. High resolution X-ray observations are needed to sort out which of the two sources is 1RXS J162620.7-332925, initially selected as a VASC candidate.

4.3. VASC J1628-41

This is a relatively bright star, which shows a strong variable Hα emission discovered in April 2001 by AAT spectroscopy (Tsarevsky et al. 2001). In contrast, the VLT spectra show

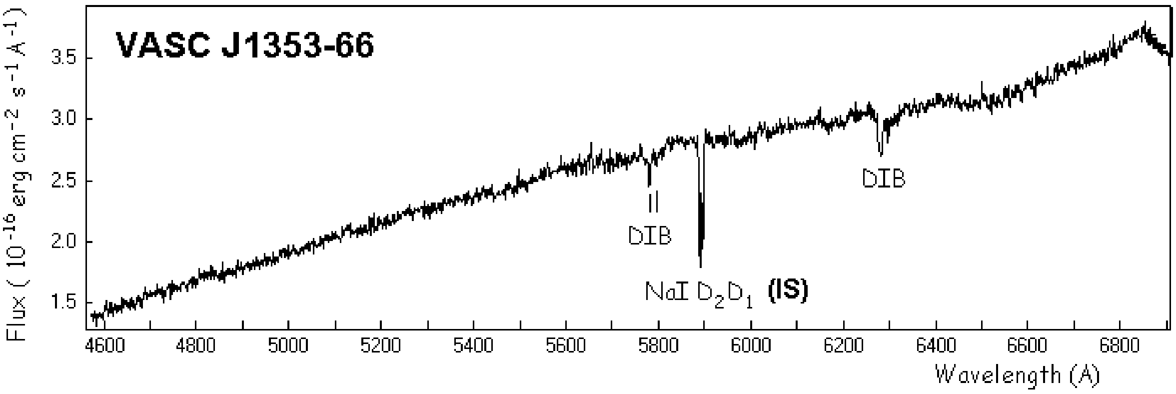

Fig. 1. Featureless spectrum VLT of VASC J1353-66. Interstellar features indicated: diffuse bands (DIB) and a NaI doublet.

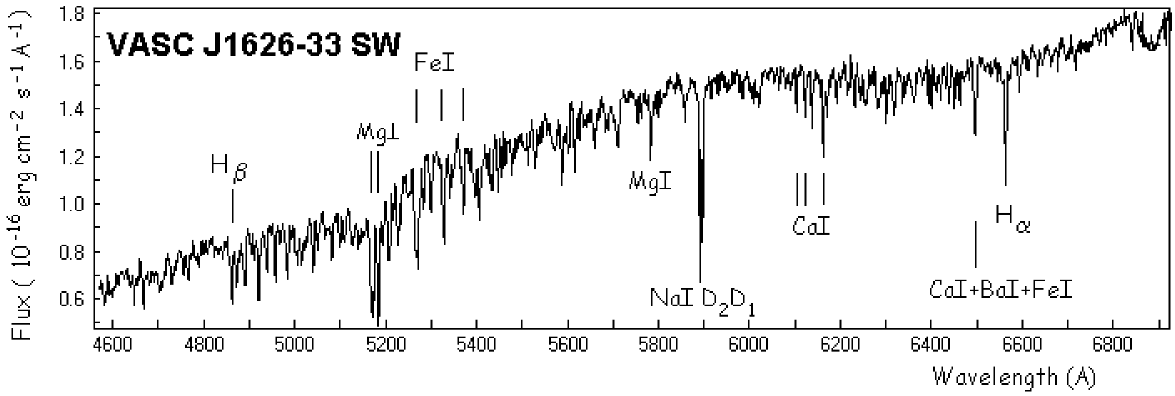

Fig. 2. VLT spectrum of the SW component of VASC J1626-33, identified as a K0 III star.

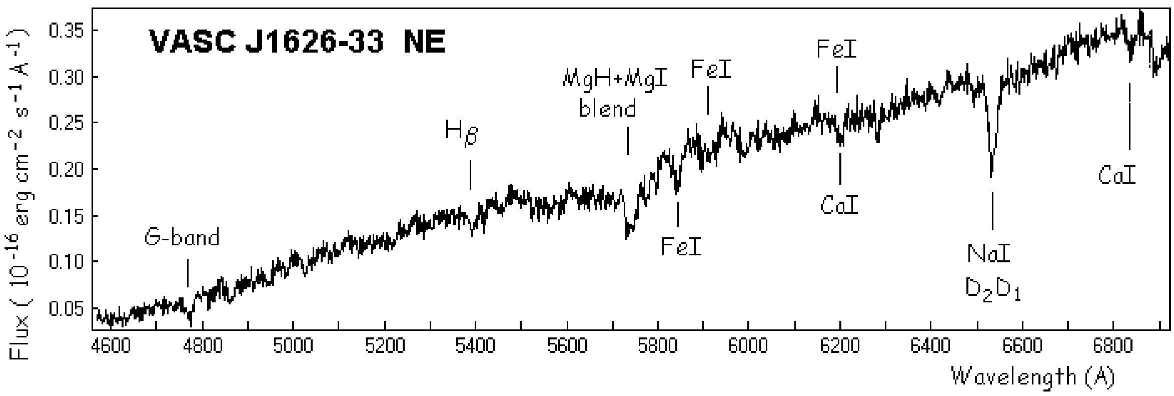

Fig. 3. VLT spectrum of the NE component of VASC J1626-33, identified as an elliptical galaxy E0 at z = 0.1092. See VLT FORS1 optical image in Fig. 4.

a weak emission and a small variation between successive nights (see Fig. 5). Corresponding equivalent widhts, *EW*, are as follows:

31-Jul.-2003 $EW = -1.04 \pm 0.08$ Å

2-Aug.-2003 $EW = -0.41 \pm 0.10$ Å.

This can be compared with the much stronger Hα emission displayed in Tsarevsky et al. (2001) by retrieving via URL:
`http://www.atnf.csiro.au/people/gtsarevs/J1628-41_Halpha.eps`

The spectrum is typical of a late metal-poor giant star. In Table 1 we adopted a spectral classification K3 III-IV made by Torres et al. (2004) using the MIKE echelle on the 6.5-m Baade telescope.

The binary nature of this star was recently suggested by Buxton et al. (2004) and confirmed by Torres et al., who assigned it to the RS CVn class. However this possibility needs confirmation by additional radial velocity data. If this object is in fact a RS CVn, it would be the hardest X-ray emitter of this class. An inverted radio spectrum (Table 2) and a transient radio

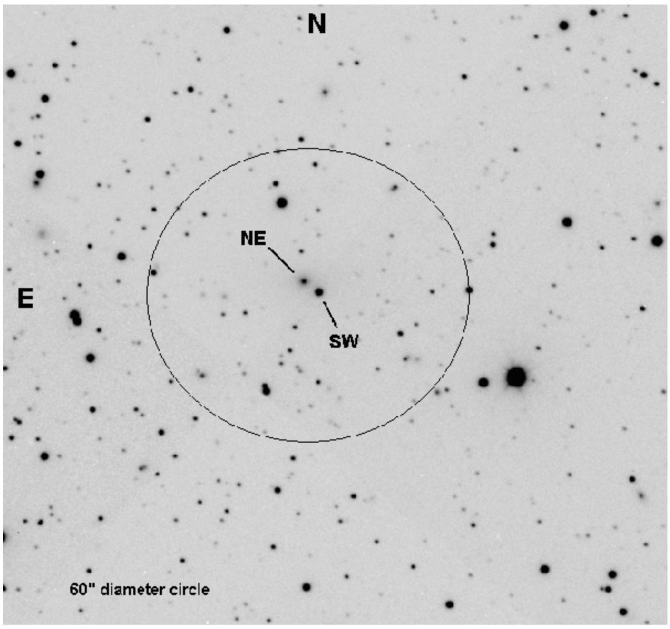

Fig. 4. FORS1 VLT *R* image for the VASC J1626-33 complex: SW (star – VAS candidate) and NE (elliptical galaxy E0 at z = 0.1092); d = 3.5″, PA = 45°.

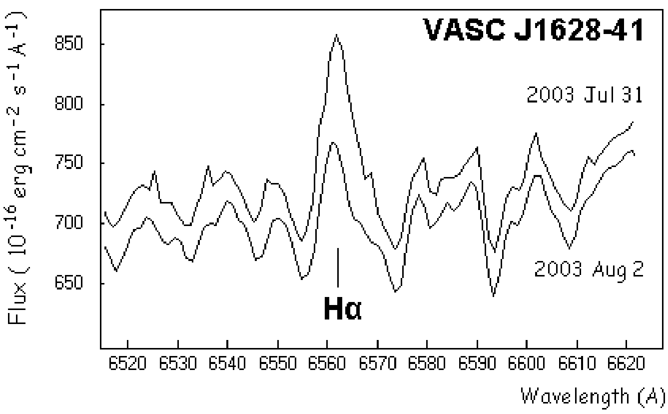

Fig. 5. VLT spectrum of VASC J1628-41 in the Hα region. Notice the Hα emission variation between two different nights (spectrum of Aug. 2 is arbitrary shifted down).

emission of VASC J1628-41 were shown by CA and VLA observations (Slee et al. 2002; Rupen et al. 2002) gives the observations, we conclude that this object is definitively a VAS.

4.4. VASC J1757-41

This object is a strong radio source with an unresolved core and a rather flat spectrum (see Table 2), and also is a star-like optical object chosen by our selection criteria. The VLT spectrum (Fig. 6) shows emission lines typical of AGN (broad Balmer lines and narrow forbidden lines, corresponding to a redshift of z = 0.3342 ± 0.0002). The full width at zero intensity of the Hβ emission is about 12 200 km s^{-1}, consistent with that of a Seyfert 1 galaxy, which in our case is seen through the plane of the Galaxy. The forbidden [OIII]λ5007 lines are quite extended, corresponding to about 8.5″ along the slit. Thus, the projected linear extent of the emitting region at the measured redshift is about 44 kpc (for a flat cosmological model with $\Omega_m = 0.3$, H_0 = 65 km s^{-1} Mpc^{-1}).

4.5. VASC J1942+10

The VLT data show a featureless spectrum similar to VASC J1353-66, with an interstellar (IS) NaI doublet and some weak diffuse interstellar bands (DIB) at 5800 Å and 6300 Å (Fig. 7). BTA data confirm the featureless spectrum of the object. Taking into account the detected X-ray and radio emission, this source is probably a new BL Lac type object behind the plane of the Galaxy.

5. Summary

In this paper we report the spectral classification of five VAS candidates with the VLT-FORS1 spectrograph, also using some of the AAT and BTA spectra. These objects are part of a complete sample of bright and hard ROSAT sources, emitting also at radio frequencies, selected in the plane of the Galaxy ($|b| < 20°$). Their unambiguous optical identifications were possible thanks to arcsec-resolution observations at 4.8 and 8.6 GHz made with the CA and VLA.

Two of the five candidates are late-type giant stars, and therefore promising VAS candidates. Their radio spectral indices (Table 2) indicate flat/inverted radio spectra characteristic of the MCQ family (see Fender 2001). One of two, VASC J1628-41, due to X ray, radio and optical behaviour, can be definitively classified as a VAS. Further optical photometry, high resolution spectroscopy and radio observations are needed to establish their variability, binarity, presence of jet, and so on.

Two other objects show featureless spectra, suggesting that they are probably new BL Lac type objects in the ZOA (like another two objects discovered in a similar way by Marti et al. 2004). Surprisingly, for one of these objects, VASC J1353-66, the NOMAD catalog indicates a small proper motion. If confirmed, it would suggest the discovery of an interesting new type of Galactic source. Indeed, the only sources in the Galaxy having continuous spectra are members of a well-known subclass of white dwarfs (WC), which do not display the distinctive radio and X-ray emission required by our criteria.

Finally, we have also found a Seyfert 1 galaxy (J1757-41) in the ZOA at z = 0.3342 ± 0.0002. This galaxy is also a strong radio source and has a star-like appearance in optical images. This case is very similar to the well-known Seyfert GRS 1734-292 behind the Galactic center, discovered and investigated by Marti et al. (1998), which was initially suspected to be a microquasar.

A statistical study including all selected and observed VAS candidates will be reported in a separate paper.

Acknowledgements. We would like to thank E. Budding, A. Burenkov, M. Buxton, L. Berdnikov, I. Karachentsev, W. Orchiston,

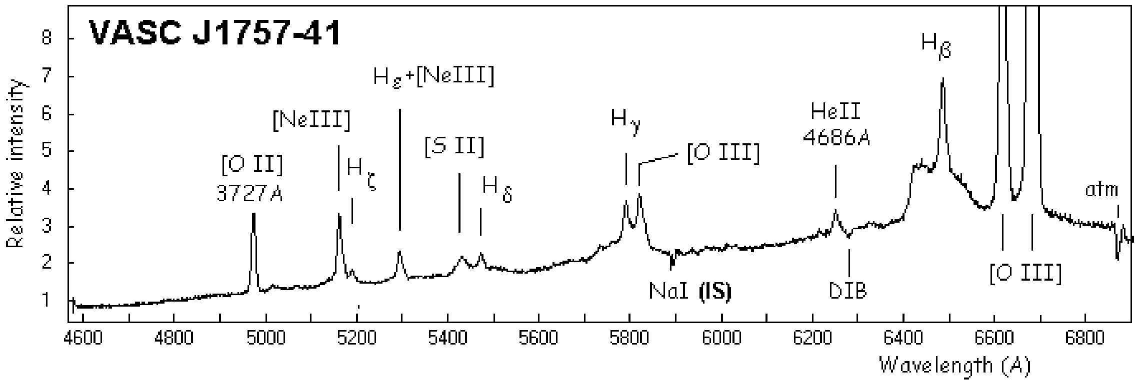

Fig. 6. VLT spectrum of VASC J1757-41, identified as a Sy 1 at z = 0.3342.

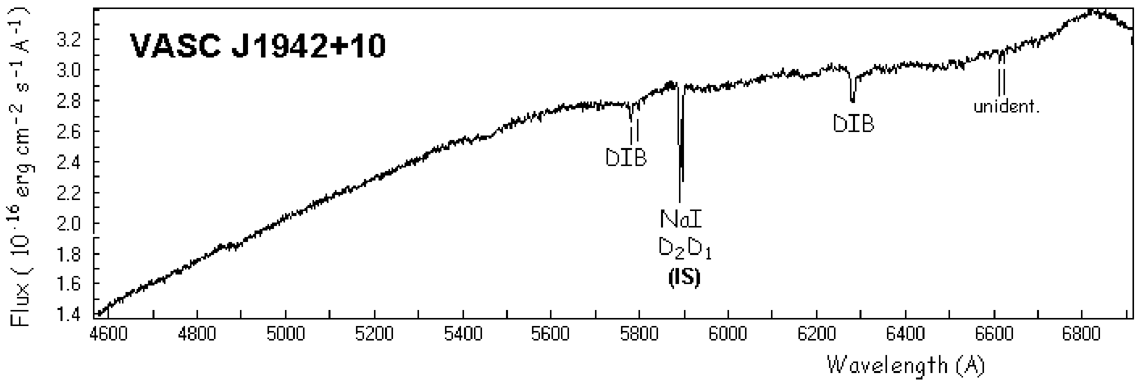

Fig. 7. Featureless spectrum VLT of VASC J1942+10. Interstellar features are indicated: diffuse bands (DIB) and a NaI doublet. Weak absorption unidentified lines near 6620 Å are also marked.

E. Pavlenko, I. Pronik, M. Rupen, R. Sault and R. Spencer for discussions and help with observations. We are indebted L. Staveley-Smith and the anonymous referee for valuable comments, that improved the earlier version of this paper. B.K. and G.T. acknowledge financial support from the Russian Federation Fundamental Research grant 03-02-16580. G.T. is indebted to colleagues of the Cote d'Azur Observatory for their hospitality and stimulating discussions during his 2003-04 visits. We acknowledge use of the SIMBAD, NED, CATS, NVSS, 2MASS and USNO databases in the Virtual Observatory regime. The Compact Array is part of the Australia Telescope, which is a National Facility of the Commonwealth of Australia managed by CSIRO.

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