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The nature of X-ray selected star candidates

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The joint HRC/BHRC catalogue of optical identifications of ROSAT BSC and FSC X-ray sources is based on merging the Hamburg–ROSAT Catalogue (HRC) and Byurakan–Hamburg–ROSAT Catalogue (BHRC). Both have been made by optical identifications of X-ray sources based on low-dispersion spectra of the Hamburg Quasar Survey (HQS) using the ROSAT Catalogues. HRC/BHRC contains a sample of 8132 (5341+2791) optically identified X-ray sources with count rate (CR) of photons ≥ 0.04 ct/s in the area of the low-dispersion Hamburg Quasar Survey (HQS), $|b| \geq 20^\circ$ and $\delta \geq 0^\circ$. Based on low-dispersion spectral classification, there are 4253 AGN, 492 galaxies, 1800 stars and 1587 unknown objects in the sample. 1800 star candidates include 1429 objects listed in SDSS DR12 photometric catalogue and 433 given in SDSS spectroscopic catalogue. Using these spectra, we have carried out classification of these star candidates to reveal new interesting objects, as well as to define the true content of our sample. 34 cataclysmic variables (including 7 new ones), 19 white dwarfs, 19 late-type stars (K-M and C types), 16 early type stars (O-B), 40 hot coronal stars (A-F types), 2 composite spectrum objects, and 17 bright stars have been revealed, as well as 286 objects which turned out to be extragalactic ones; 75 emission-line galaxies (HII/SB and AGN, including QSOs, Seyferts, and LINERs) and 211 absorption line galaxies were revealed (wrong classifications in HRC/BHRC due to their faint images and low-quality spectra). We have retrieved multiwavelength data from recent catalogues and carried out statistical investigations of the multiwavelength properties for the whole sample of stars. All stars have been found in GSC 2.3.2, as well as most of them are in GALEX, USNO-B1.0, 2MASS and WISE catalogues. Relations between the radiation fluxes in different bands from X-ray to radio for different types of sources are studied and analysis of their characteristics is made. X-ray selected stars are an important complement to the stellar populations of our Galaxy in solar neighbourhood and beyond.

Keywords: X-ray sources, cross-correlations, white dwarfs, cataclysmic variables, carbon stars

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1 Introduction

X-ray sources provide new additional data for overall studies of objects known before in optical, UV, IR or radio domains but still having missing characteristics or physical properties to be revealed. ROSAT catalogues contain thousands of interesting objects, including AGN, hot subdwarfs, white dwarfs (WDs), cataclysmic variables (CVs), carbon (C) stars, etc. Though a number of recent X-ray missions have been conducted (XMM-Newton, Chandra, etc.), ROSAT so far remains the only all-sky deep enough survey. ROSAT sources are listed in two main catalogues:

Bright Source Catalogue (BSC; Voges et al. 1999) and Faint Source Catalogue (FSC; Voges et al. 2000). ROSAT BSC contains 18,806 sources with CR $\geq$ 0.05 cts·s^{-1} in the 0.1–2.4 keV energy range, while ROSAT FSC contains 105,924 fainter sources (CR $\leq$ 0.05 cts·s^{-1}). Thus, in total 124,730 sources are available.

Among the identification works, the ROSAT Bright Sources (RBS, Schwope et al. 2000) is well-known; 2012 BSC sources with CR $\geq$ 0.20 and $|b| > 30^\circ$ have been optically identified. However, most of the identified sources come from the Hamburg Quasar Survey (HQS, Hagen et al. 1995). Its low-dispersion spectra allow us to make a preliminary classification of objects into a number of types, giving the possibility to make up subsamples of objects for further studies. Two main projects have been carried out: Hamburg ROSAT Catalogue (HRC, Zickgraf et al. 2003) and Byurakan–Hamburg ROSAT Catalogue (BHRC, Mickaelian et al. 2006). Both have been carried out by means of Hamburg Quasar Survey (HQS; Hagen et al. 1995) low-dispersion spectra. HRC is based on ROSAT BSC and contains 5341 sources at $|b| > 20^\circ$ and $\delta > 0^\circ$, while BHRC is based on ROSAT FSC and contains 2791 fainter sources (down to CR = 0.04) in the same area (3297 objects found). Thus, out of 124,730 ROSAT sources, only ∼10,000 have optical identifications and ROSAT catalogues still remain as a rich source for new interesting objects.

A Joint HRC/BHRC Catalogue has been created by merging HRC and BHRC, altogether 8132 sources (Paronyan & Mickaelian 2015). Together with combining data from the two catalogues, we have checked and added many new ones, as well as corrected many errors and misidentifications. In BHRC, the number of objects in most of types are similar to those in HRC, however, we have tried to classify most of the bright stars as well, and as a result, we have a very small number of bright stars left (3.3% compared to 22.8% in HRC) and a lot of classified stars (30.1% compared to 8.5% in HRC). In addition, a larger number of associations has been classified, and most of the analogues of unidentified objects in HRC turned to be faint AGN in BHRC. Therefore, these numbers (41.5% in HRC and 54.5% in BHRC) are quite different. After new verifications and corrections in the Joint HRC/BHRC, we have the final distribution of types of identified objects.

Thus, we have 4253 AGN and their candidates, 492 galaxies, 1800 stars and 1587 unidentified objects in the whole sample. In this paper, we carry out some preliminary studies of 1800 objects of the "Stars" sample, including spectroscopic classification based on SDSS DR12 (Alam et al. 2015). Among the 1800 "stars", based on our low-dispersion classification, we have 919 bright stars (without an exact spectral type due to saturation of bright images on HQS plates), 62 WDs, 35 CVs, 327 AFG type stars, 310 K type stars, and 147 M/C type stars, a rich material for further studies.

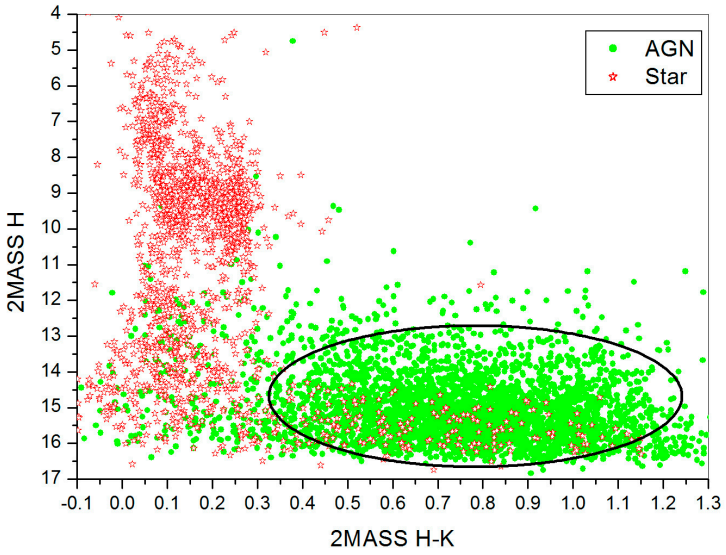


Figure 1 Multiwavelength colour-magnitude diagram based on 2MASS to distinguish stars from galaxies.

2 Multiwavelength data

We have cross-correlated the Joint HRC/BHRC sources with recent all-sky and large area catalogues from γ-rays to radio: FERMI (Acero et al. 2015), INTEGRAL (Bird et al. 2010), GALEX (Bianchi et al. 2011), APM (McMahon et al. 2000), USNO-B1.0 (Monet et al. 2003), GSC 2.3.2 (Lasker et al. 2008), SDSS DR12 photometric and spectroscopic (Alam et al. 2015), 2MASS (Cutri et al. 2003), WISE (Cutri et al. 2012), AKARI IRC (Ishihara et al. 2010), IRAS PSC and FSC (IRAS 1988; Moshir et al. 1992), AKARI FIS (Yamamura et al. 2010), NVSS (Condon et al. 1998), and FIRST (Helfand et al. 2015), as well as with the Catalogue of QSO and AGN, 13th version (VCV-13, Véron-Cetty & Véron 2010), Roma Catalogue of Blazars (BZCAT; Massaro et al. 2015), catalogues of white dwarfs (McCook & Sion 2008; Kleinman et al. 2013) and cataclysmic variables (Ritter & Kolb 2014). These multiwavelength (MW) data allow us a full understanding of these objects, as well as an analysis of their color–magnitude and color–color diagrams. Figure 1 gives such diagrams showing reliable distinguishing of stars from galaxies. We distinguish with ellipses the main regions of location for AGN. However, one can notice that most active stars (CVs and WDs) show evidence of grouping with AGN and other galaxies.

Table 1 gives the listing of all recent MW and dedicated (AGN, WD and CV) catalogues with the numbers of corresponding associated objects, as well as photometric bands that can be used for further MW studies. Thus, typically we have 37 photometric bands for each object (excluding Fermi-GLAST, INTEGRAL, IRAS, AKARI and NVSS/FIRST having small number of associations for stars, we have 18 points for most of the objects) and for many of them, medium resolution 3800–9200 Å spectra.

Table 1 Multiwavelength data for X-ray sources from the Joint HRC/BHRC catalogue.

Catalogues	Search radius (arcsecond)	Star	Photobands, spectral range
Fermi-GLAST	600	17	0.1–0.3, 0.3–1, 1–3, 3–10, 10–100 GeV
INTEGRAL	600	1	10, 30, 60 keV
ROSAT BSC/FSC	40	1800	0.07–2.4 keV
GALEX	3	918	FUV 1528A, NUV 2271A
APM	4	1387	b 4050, r 6452
USNO-B1.0	4	1788	B 4050/4680, R 6452, I 8060
GSC 2.3.2	4	1800	bj 4680, F 6452, N 8060
SDSS DR12 photo	2	1429	u 3551, g 4686, r 6165, i 7481, z 8931
SDSS DR12 spectro	2	433	3800–9200 (3500–10500) Å
2MASS	2	1585	J 1.24, H 1.66, Ks 2.16 mm
WISE	2	1485	w1 3.4, w2 4.6, w3 11.6, w4 22 mm
AKARI IRC	10	171	9, 18 mm
IRAS PSC/FSC	60	102	12, 25, 60, 100 mm
AKARI FIS	5	0	65, 90, 140, 160 mm
NVSS	10	9	21 cm (1.4 GHz)
FIRST	3	6	21 cm (1.4 GHz)
WDs	60	53	Spectral types, optical photometry, etc.
SDSS WDs	2	13	Sp types, SDSS photometry, PM, etc.
CVs	60	52	Spectral types, optical photometry, etc.
Total		1800	

3 Stars sample in merged HRC/BHRC

As mentioned, MW colour–magnitude and colour–colour diagrams have been used to distinguish stars from galaxies, also all available databases have been searched for object types. In Fig. 2 we also use X-ray properties to find the stars against galaxies (AGN). X-ray and radio flux ratio vs. X-ray flux diagram has been used. All non-classified sources have been grouped into candidate stars, galaxies, and AGN. As for Fig. 1, here we also distinguish with an ellipse the main region of location for AGN.

Out of 1800 objects in the "stars" sample, according to HQS classification and revised types from available catalogues, we have 44 bright stars (saturated images not allowing classification for stellar types), 61 WDs, 35 CVs, 4 B type stars, 3 BA, 23 A type, 30 AF, 100 F type stars, 327 FG, 145 G, 34 GK, 386 K, 22 KM, 223 M, 1 C (carbon) star; 73 extremely blue weak objects (candidate WDs, CVs or AGN), 55 blue weak objects (also candidate WDs, CVs or AGN), 152 red weak objects (candidate late-type stars), 1 planetary nebula (PN), and 5 overlaps not allowing any classification, as well as 58 misclassified objects (42 QSOs, 10 AGN, and 6 blue galaxies, also most probably AGNs). Other objects do not have any classification and appear in "stars" sample due to their stellar images.

All 1800 stars have been found in GSC 2.3.2, as well as most of them are in GALEX (918), APM (1387), USNO-B1.0 (1788), 2MASS (1585) and WISE (1485) catalogues. Some WDs and CVs have been also found in γ rays. 102 stars (bright and late-type ones) have been also found in IRAS. In addition, 1429 are in SDSS DR12

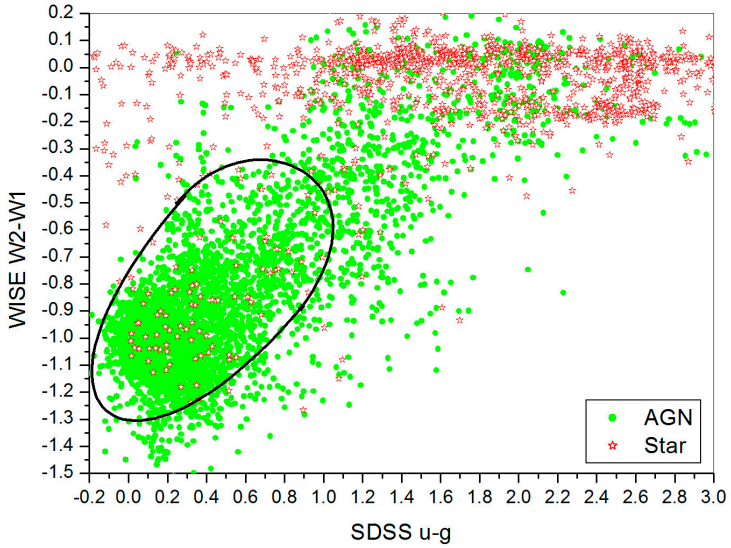


Figure 2 Multiwavelength color–color diagrams based on SDSS and WISE to distinguish stars from galaxies.

and 433 have SDSS spectra. For these stars we have carried out spectral classification and along with the bright stars, many new CVs, WDs and late-type stars (K-M and C) have been revealed.

For all stars, statistical studies of their multiwavelength properties have been made. We give in Fig. 3 X-ray and SDSS r flux ratio vs. X-ray flux diagram to

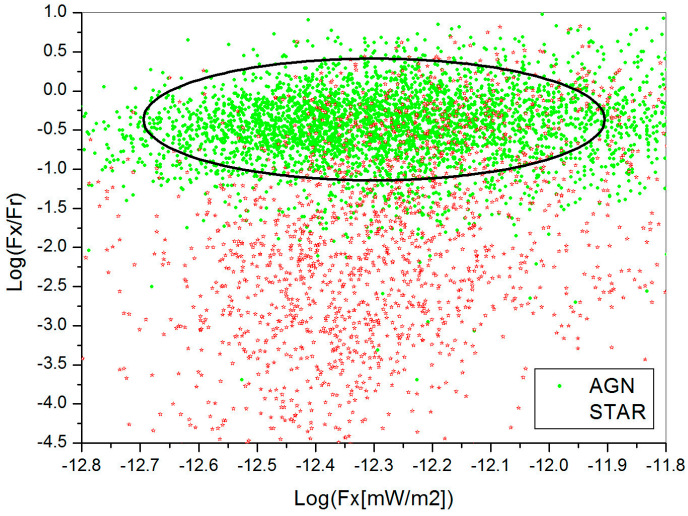


Figure 3 X-ray and SDSS r flux ratio vs. X-ray flux diagram to distinguish stars from galaxies.

distinguish stars from galaxies. Galaxies have higher F_x/F_r and only some special types of stars (WDs, CVs) show similar ratios. An attempt to find a connection between the radiation fluxes in different bands for different types of sources, and to identify their characteristics was made as well. In the following subsections we give short descriptions of each stellar subsample and examples of SDSS spectra.

3.1 Bright FG-type stars

During the course of identifications, we have found many bright FG stars, which are not strong X-ray emitters but appear in ROSAT due to their brightness, so that many bright stars even without any peculiarity have been detected by ROSAT. An important question is to estimate the limiting magnitude for each colour index to establish the limiting curve for detection in ROSAT. In Fig. 4, we give 2 examples of bright FG type stars, classified by means of SDSS spectra. Their spectra are characterized by strong absorption Mg, Na and Balmer lines.

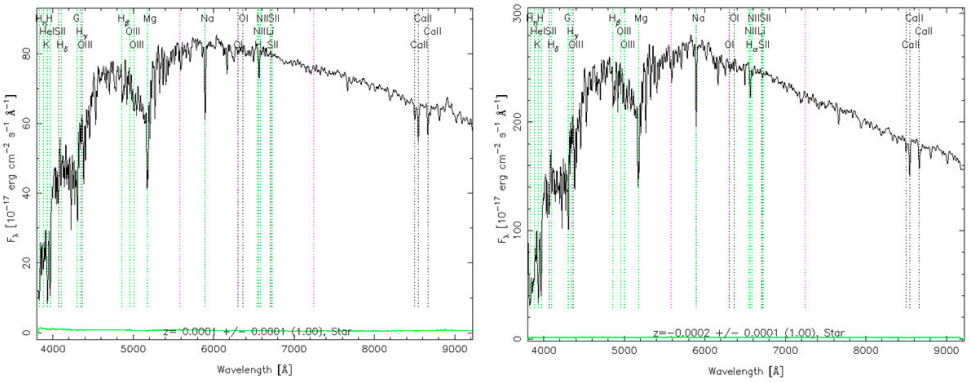


Figure 4 Two examples of bright FG-type stars classified by means of SDSS spectra.

3.2 Cataclysmic variables and X-ray binaries

Cataclysmic Variables (CV) have a number of subtypes, including classical Novae (N), recurrent Novae (Nr), Dwarf Nova (DN), Nova-Like (NL) variables, Polars, Intermediate Polars (IP), Low Accretion Rate Polars (LARP), Low-Accretion Rate Intermediate Polars (LARIP), and some others.

CVs or Cataclysmic Binaries (CB) are among the strongest X-ray sources. They are supersoft X-ray sources. CVs are semi-detached binaries: they contain primary component, WD or a WD precursor and secondary component, a low mass main sequence normal (mainly K or M type) star. The components are so close to each other that WD's gravitation destroys the secondary, which causes outflow of matter to WD; the latter accretes matter from the secondary via Roche lobe overflow (as in these systems the secondary is filling its critical Roche lobe). In *magnetic CVs* the WD is a magnetic WD, and CVs with most powerful magnetic fields are called AM Herculis type stars or *polars*. There also are CVs with intermediate strength magnetic

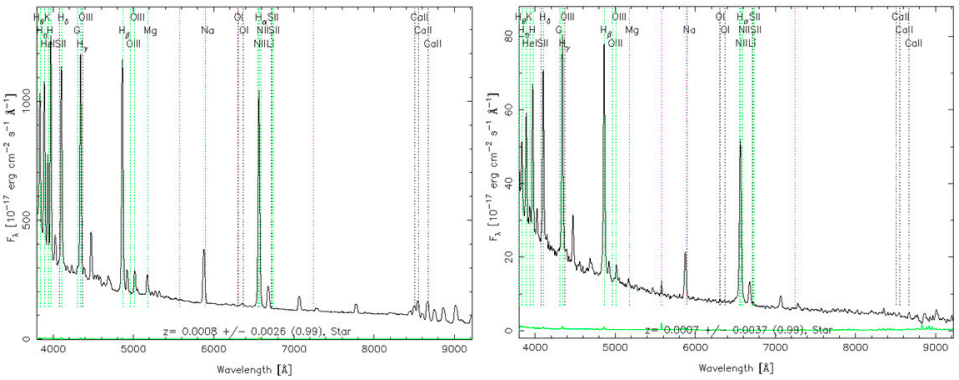


Figure 5 Two examples of cataclysmic variable (CV) classified by means of SDSS spectra.

fields; these are DQ Herculis type stars or *intermediate polars*. *Magnetar* is a class of NS with extremely powerful magnetic field. Their magnetic fields reach 10^8–10^{11} Teslas. *Low-Mass X-Ray Binaries* are semi-detached binaries having significant X-ray radiation. X-ray is produced by the matter falling from one component to the other; the first is called donor (typically a normal star, low-mass secondary which is filling its critical Roche lobe) and the second, accretor (a compact star; WD, *neutron star*, NS, or *black hole*, BH). *Intermediate Mass X-ray Binary* (IMXB) is a star system, where one of the components is a neutron star or black hole, and the other is intermediate mass star. *CV Related Objects* are detached binaries consisting of either a WD or a WD precursor primary and of a low-mass secondary. The secondary may also be a highly evolved star.

Most complete list is given in the catalogue of Cataclysmic Binaries, LMXBs, and related objects (Ritter & Kolb 2014); 1166 cataclysmic binaries, 105 low-mass X-ray binaries and 500 related objects. There are 35 types and subtypes of CVs given in this catalogue.

On the basis of HQS low-dispersion spectra, 18 were classified as CVs and out of them 14 really turned to be genuine CVs. But in addition, CVs are found among objects classified as blue weak or extremely blue weak ones, as well as QSOs or AGN. Out of 34 objects in our sample, classified as CVs by means of SDSS spectra, 7 appear to be new ones, absent in Ritter & Kolb (2014). Among the known ones, most popular subtypes are DN SU and NL AM ones. In Fig. 5, we give 2 examples of CVs classified by means of SDSS spectra. Their spectra are characterized by strong Balmer and sometimes HeI and HeII emission lines.

3.3 White dwarfs

White Dwarfs (WD), NSs and BHs are the late stages of stellar evolution. These are stars consisted of electronic degenerate gas and are often called degenerate dwarfs. Their mass is close to Solar and their sizes are close to terrestrial, hence their high densities. WDs are also very faint: they radiate stored thermal energy, however they are very hot in early stages and also radiate X rays. According to the theory, 97%

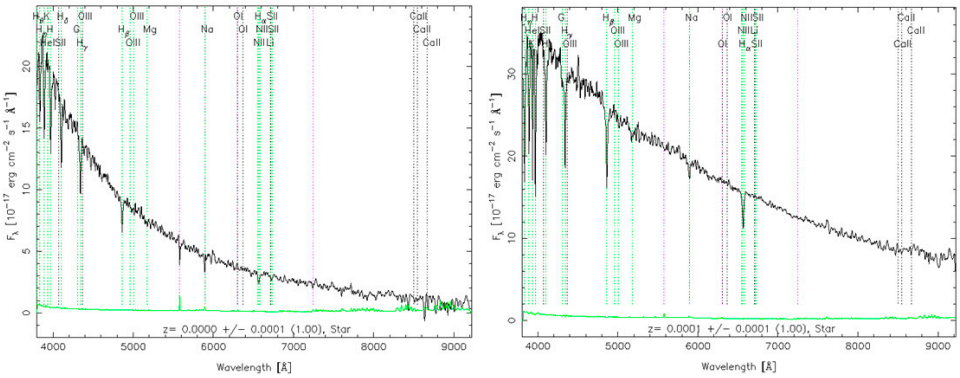


Figure 6 Two examples of white dwarfs (WD) classified by means of SDSS spectra.

of stars of our Galaxy will turn to WDs, as their mass is not enough to explode as supernova and to turn to NS or BH. WDs have powerful magnetic fields, up to 100 mln Gauss (100 Tesla), and their about 10%, called *magnetic WD*, have 100–100,000 Tesla magnetic fields (to compare, Earth's magnetic field variates within 30–60 microtesla range). The most complete catalogues of WDs are the Catalogue of Spectroscopically Identified White Dwarfs (McCook & Sion 2008; 20,602 WDs from the whole sky) and SDSS DR7 White Dwarf Catalog (Kleinman et al. 2013; 20,407 WDs in SDSS area of 14,555 deg^2). Their optical spectra show mainly broad absorption Balmer lines and sometimes HeI and/or HeII lines (Fig. 6).

3.4 Early-type stars

Some of *hot subdwarf* stars also are X-ray sources, as they also have high surface temperatures and strong magnetic fields. Other early-type stars include OB spectral types, and *Horizontal Branch B (HBB)* stars. Figure 7 presents two examples of early-type stars having X-ray emission, a possible HBB (left) and a sdB type subdwarf (right).

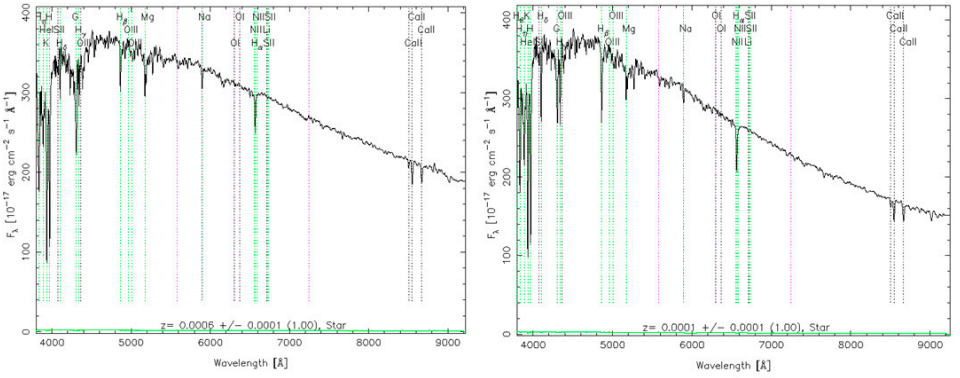


Figure 7 Two examples early-type stars, classified by means of SDSS spectra.

3.5 Hot coronal stars

Hot Coronae. There are stars having coronae or coronal envelopes, whose coronal heating is explained as in the case of the Sun by magnetic fields and also is connected to their rotation period. As a rule, main sequence coronal stars are late A or early F type stars. We give in Fig. 8 two examples of hot coronal AF stars classified by means of SDSS spectra. Their spectra are characterized by deep Balmer and other absorption lines, G band, and especially deep CaH and K doublet at UV.

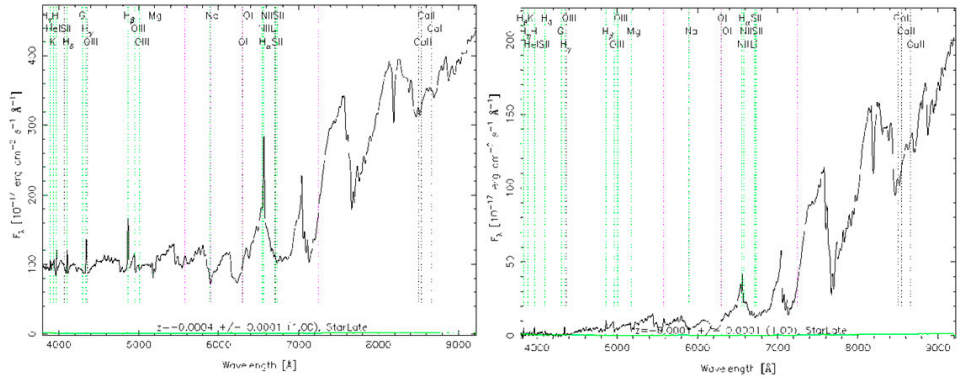


Figure 8 Two examples of hot coronal stars, classified by means of SDSS spectra.

3.6 Late-type stars

Among X-ray stars there also are many *K-M type giants* (Hunsch et al. 1998). Being at the late phases of evolution, their outer layers are expanding and these extended coronae may produce powerful X rays. *Late (M) type dwarfs*, as a rule are dwarf stars of M5 and later subtypes, whose inner structure significantly changes. They become completely convective. Surface magnetic flows and topology in coronal magnetic fields change causing changes of X-ray properties. Their optical spectra are characterized by hydrogen Balmer line emission, as well as strong molecular absorption bands of TiO, CaH, and MgH (Fig. 9). Strength of the CaII H and K and HI emission lines is a good indicator of the level of chromospheric activity (Petterson & Hawley 1989). Often flare stars are observed among them, whose brightness increases several times in the flare phase. They resemble Solar flares, however they are a few orders of magnitude more powerful. X-ray fluxes of these stars originate in the chromosphere and corona, where the magnetic energy generated by the dynamo action is dissipated (Mathioudakis et al. 1995). In Fig. 9, two examples of late-type X-ray emitters are given: K-type star with overlapped Balmer emission lines (left) and M-type star (right).

3.7 Composite spectrum objects

Among X-ray candidate stars of our sample there also exist objects having composite spectra as a contamination of different spectral type stars. The number of objects

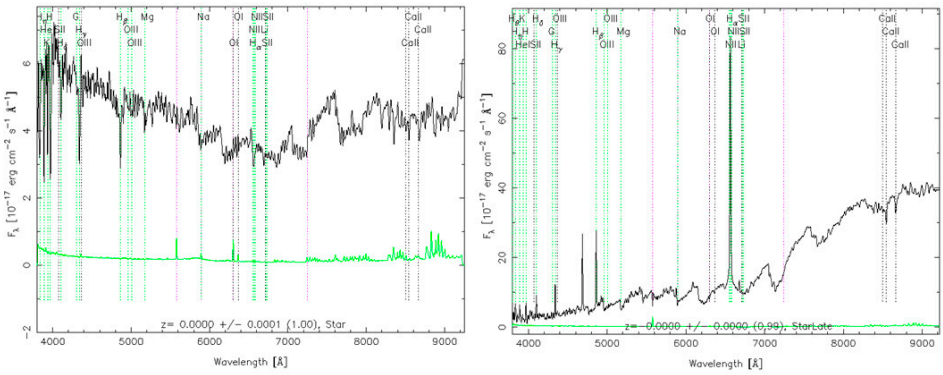


Figure 9 Two examples of late-type stars, classified by means of SDSS spectra; (left) K-type star with overlapped Balmer emission lines and (right) M-type star.

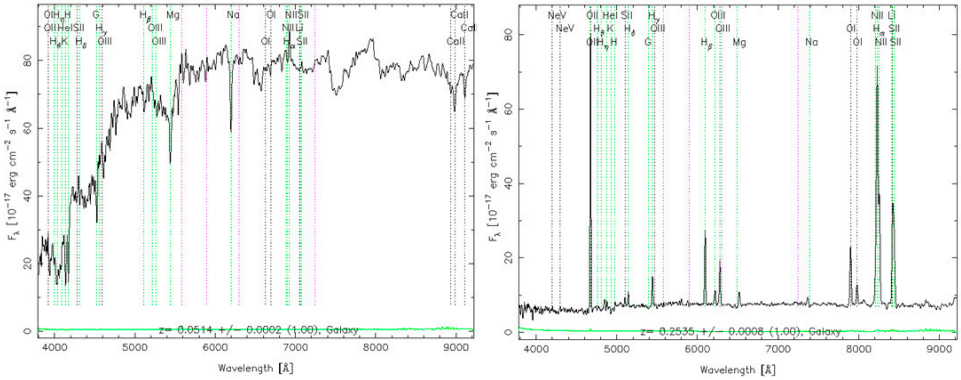


Figure 10 Two examples of composite spectrum objects, classified by means of SDSS spectra.

with composite spectrum is only 2. In Fig. 10 we present these two examples of composite spectrum objects classified by means of SDSS spectra; a superposition of early and late type stars (left) and a superposition of emission line spectrum over a late-type (K) star molecular bands.

3.8 Misclassified objects: galaxies

Objective prism surveys classification may cause some errors, as one can notice only most prominent features in the low-dispersion spectra. After checking our classification with recent data, we have revealed a number of extragalactic objects, which erroneously appear in our "Stars" sample. These misclassified objects are galaxies and QSOs. In Fig. 11 we give two examples of galaxies (absorption and emission ones), classified by means of SDSS. This subsample is subject of another study and will be given in other paper.

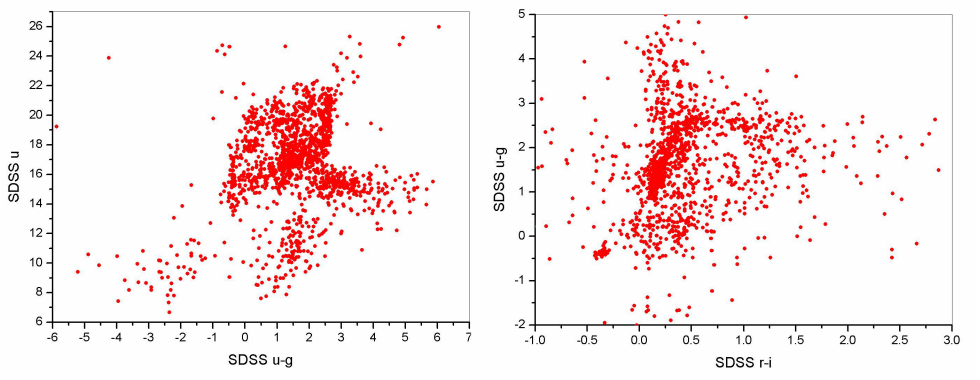


Figure 11 SDSS u-g vs colour-magnitude diagram (left) and SDSS r-i vs u-g colour-colour diagram (right) for HRC-BHRC stars showing different locations for different types.

4 Statistical analysis of the stellar content

As mentioned, out of 1800 objects in the "Stars" sample, 433 have SDSS DR12 spectra. We have classified them into 9 types (Table 2). In the last two columns we give the fraction of objects in respect of the total number (433) and the number of stars (147), respectively. A large number of misclassified objects mainly concerns faint magnitudes and even from SDSS spectra it is difficult to carry out an accurate classification. Not counting misclassified objects, out of 147 genuine stars we have even distribution among the bright stars, most interesting CVs and WDs, early-type and late-type ones.

However, as not all stars have SDSS (or any other) spectral classification, we carry out some statistical analysis (graphical distribution of various data) to find out the properties of ROSAT catalogues stellar content. We have used all possible multi-

Table 2 Distribution of stellar types and misclassified objects in the HRC/BHRC "Stars" sample.

Type / Description	Number	Fraction(%)	
		All objects	Stars
Bright Stars	17	3.93	11.56
CV and Related Objects	34	7.85	23.13
WDs	19	4.39	12.93
Early-Type Stars	16	3.70	10.88
Hot Coronal Stars	40	9.24	27.21
Late-Type Stars	19	4.39	12.93
Composite Spectrum Objects	2	0.46	1.36
AGNs (Emission-Line Galaxies)	75	17.32	
Absorption-Line Galaxies	211	48.73	
All Objects	433	100.00	100.00

wavelength data to build color-magnitude and color-color plots or flux ratios. Such diagrams are rather efficient to distinguish definite types of objects. Most efficient (and most accurate) data that provide relevant results are SDSS, 2MASS, and WISE photometric data. In Fig. 11 we give only two examples of such plots, namely SDSS u-g vs. u color–magnitude diagram (left) and SDSS r-i vs. u-g color–color diagram (right). For the study of the whole stellar content, we will use these plots to distinguish between different types of stars.

5 Summary and future studies

We have cross-correlated HRC and BHRC and compiled a Joint HRC/BHRC Catalogue of ROSAT identifications, where 8132 sources are listed, including 4253 AGN and candidates, 492 galaxies, 1800 stars and 1587 spectroscopically unidentified objects. Among 1800 X-ray stars, we have bright stars, WDs, CVs, early-type stars, hot coronal emitters, late-type stars, as well as misclassified objects (AGN and galaxies). We have collected all available MW data for all these sources from γ-rays to radio and constructed various diagrams to investigate their physical properties. Stars strongly differ by their X-ray properties (hardness ratios, f_x/f_{opt} and f_x/f_{NIR})from AGN and galaxies, though CVs and WDs show properties close to AGN. 433 objects in "Stars" sample have SDSS DR12 spectra that allowed us spectroscopically classify them. This way we have found a number of new objects, though we have also found many misclassified galaxies that have appeared in stellar sample. X-ray stars are subject for further studies to investigate their physical characteristics and compare to the similar types without a strong X-ray emission.

With this paper, a project on study of X-ray selected stars has been conducted in BAO. It includes selection, cataloguing, spectral classification, multiwavelength studies and statistical analysis of such objects. Follow-up programs and future tasks include: estimation of ROSAT BSC/FSC stellar content, statistical study of the whole ROSAT ROSAT BSC/FSC stellar sample, detailed spectroscopic study of newly discovered stars and a number of other dedicated studies of definite types of objects (variability study of CVs, polarization of WDs, variability and NIR study of late-type stars, etc.). These results will be published in our future papers.

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