Identifying new narrow-line Seyfert 1 galaxies and white dwarfs from the second ROSAT all-sky survey catalogue

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Abstract. The second ROSAT all-sky survey source catalogue (2RXS) has now been released. From the ~135 000 sources in this catalogue, a selection of sources has been made with power law photon indices steeper than 3. This resulted in a sample of 1025 sources, representing the softest sub-sample of the 2RXS catalogue (ss2RXS). These selection criteria were chosen with the purpose of potentially identifying a new sample of narrow-line Seyfert 1 galaxies (NLS1s). However, there are also other sources with similar X-ray properties: mostly white dwarfs (WDs), but also some other bright stars. A conclusive distinction can be made between the different classes by means of optical spectroscopy, but in order to perform a pre-classification, existing archival data was utilized. A pre-classification system based on AllWISE infrared magnitudes and colours was developed, providing a reliable method of distinguishing NLS1s from WDs. We can thus obtain a preliminary classification for most of the unidentified sources in the ss2RXS sample, providing a basis for the planning of follow-up spectroscopic studies.

1. Introduction

Seyfert galaxies are mostly spiral galaxies, hosting an active galactic nucleus (AGN). Seyfert galaxies are classified as either Type 1, with both broad and narrow emission lines, and Type 2 with only narrow lines (e.g. [1, pp. 140-142]). The broad lines (full-width half maximum or FWHM~1000-10000 km s^{-1}) are formed in the broad line region (BLR), which is believed to be a region of rapidly moving clouds close to the black hole. The narrow lines (FWHM~300-500 km s^{-1}) are formed in the less dense, lower-velocity narrow line region (NLR) much further away from the black hole. The accretion disc is surrounded by a big dust torus. For Type 2, the AGN is observed from the side, with the BLR obscured by the torus. For Type 1, the observer looks more or less face on towards the disc, seeing both the NLR and BLR.

Narrow-line Seyfert 1s (hereafter NLS1s) form a subclass of Seyfert galaxies (e.g. [2]). The two general defining criteria for NLS1s are: (i) the broad components of the Balmer emission lines are narrower than in the classical broad-line Seyfert 1s (BLS1s), with $\mathrm{FWHM}_{\mathrm{H}\beta\mathrm{br}} < 2000$ km s^{-1} (in fact, they are only slightly broader than the forbidden lines such as [O III], [N II] and [S II]), and (ii) the forbidden [O III] λ5007 emission is quite weak, with the ratio $\mathrm{R}_{5007} = \mathrm{EW}_{[\mathrm{OIII}]}/\mathrm{EW}_{\mathrm{H}\beta}$ being smaller than 3 (EW=equivalent width) [3, 4]. NLS1s often exhibit strong Fe II emission, e.g. the multiplets at 4570, 5190 and 5300 Å, anti-correlated with $EW_{[OIII]}$ and $FWHM_{H\beta br}$. It was also suggested that a more meaningful distinction can be made between NLS1s and BLS1s by using the strength of the Fe II λ4570 blend between 4434 and 4684 Å, with $R_{4570} = EW_{FeII\lambda4570}/EW_{H\beta} > 0.5$ for NLS1s [5].

AGNs are characterized by emission over an extremely wide range of energies in the electromagnetic spectrum, from radio to gamma-ray, including strong X-ray emission (e.g. [6, Chapter 14]). The X-ray spectra are usually fitted with a power-law, with typical values of the photon index Γ in the ~1.5-2.5 range (e.g. [7] and references therein). In figure 8 of [8], Γ is plotted versus $FWHM_{H\beta}$ for Seyfert 1s. Below a FWHM of 2000 km s^{-1}, the photon index rises from ~2.3 up to ~5. This plot also illustrates that objects with photon indices above ~3 are almost exclusively NLS1s, making X-ray selection a very robust method to find new NLS1s.

NLS1s are thought to be quite young AGNs in their early evolutionary stages [9], harbouring low- or intermediate-mass black holes [10] accreting at rates as high as 10%-100% of the Eddington rate or even higher [11]. NLS1s thus represent an important link with the intermediate mass black holes, which have not been studied well so far. The very steep soft X-ray spectra of NLS1s are in fact due to their smaller black hole mass, and high accretion rates.

While for $\Gamma \gtrsim 3$ the BLS1s are not included in the sample, such a soft X-ray sample can also be expected to include another major source class, i.e. white dwarfs (WDs) (e.g. [12]). X-ray spectra of isolated WDs are characterized by very soft emission, which can be parametrized with blackbody models with typical temperatures of $kT \sim$ 20-100 eV. Therefore, only the Wien tail of the spectrum is detected by the ROSAT PSPC, which cannot be distinguished from a steep power law due to insufficient energy resolution. This also applies to WDs in binaries, including interacting binaries like cataclysmic variables, where the accretion process is also associated with soft X-ray emission, and supersoft X-ray sources, where the nuclear burning of accreted hydrogen on the WD surface yields a high supersoft X-ray flux (e.g. [6, Chapter 10]).

In this paper, we describe the search for sources with unusually soft X-ray spectra, by utilizing the $\Gamma \gtrsim 3$ threshold in the second ROSAT all-sky survey source (2RXS) catalogue. In §2, a summary of the 2RXS catalogue is presented, together with a description of the selection of its softest sub-sample (the ss2RXS sample). In §3, the AllWISE infrared properties of confirmed NLS1s and WDs samples are described, followed by a discussion of how these properties can be used to distinguish NLS1s from WDs among unidentified sources in the ss2RXS sample. Our preliminary results for the ss2RXS sample is presented in §4, with the final conclusions in §5.

2. The 2RXS catalogue, and the selection of the ss2RXS sample

The 2RXS catalogue [13] is the second publicly released ROSAT catalogue of point-like sources detected during the ROSAT all-sky survey observations between June 1990 and February 1991, and contains ~135 000 reliable source detections. The photon event files from the ROSAT all-sky survey have been re-analysed. The main goal was to create a catalogue of point-like sources, which is more reliable than the 1RXS catalogue [14, 15]. The reliability of detections was improved by an advanced detection algorithm and a complete screening process. With the publication of the 2RXS catalogue and its data products, the detailed science specific exploration is now available for the astrophysical community. The 2RXS is the deepest and most reliable X-ray all-sky survey catalogue before the launch of eROSITA.

New data products were created to allow timing and spectral analysis. Three different spectral models were fitted to the spectrum of each source: (i) a power law, (ii) an optically thin plasma emission model, and (iii) an optically thick blackbody model. The best-fit parameters for each model, with their associated errors, are also available in the released catalogue. The most interesting objects were listed in terms of their timing and spectral properties. The science themes include (i) AGN physics (timing and spectral properties down to the lowest fluxes, multi-wavelength properties, optical follow-up programmes with e.g. SDSS data); (ii) normal galaxies (spectral properties, galaxy interactions); (iii) Galactic binaries, cataclysmic variables, neutron stars; (iv) timing properties from individual light curves of stars, and (v) search for ultra-soft X-ray emitters.

Following the motivation given in §1, a selection of sources was made from the main 2RXS catalogue, using the criteria of $\Gamma \geq 3$ for the power law fit, and the error in the best fit Γ-value also had to be smaller than 1.5. This yielded a sample of 1025 objects, representing the softest source sample from 2RXS (the ss2RXS sample).

3. AllWISE colours

It is well known that infrared colours provide a powerful method of distinguishing AGNs from other objects (see e.g. the work of [16]). Since the ss2RXS sample is expected to contain a substantial amount of NLS1s and WDs, a comparison of the infrared properties of known samples of these two classes was performed. The goal of this initial investigation was to evaluate the possibility of distinguishing between NLS1s and WDs by using only infrared properties.

3.1. The AllWISE colours of spectroscopically confirmed NLS1 and WD samples

The Sloan Digital Sky Survey (SDSS) provides photometric and spectroscopic data for a large fraction of the sky, making it a very powerful survey for identifying and studying large samples of sources from different object classes. The number of known NLS1s was increased by a factor of ∼10 in 2006 with the publication of a sample of 2011 confirmed NLS1s from the spectroscopic sample of the SDSS Data Release 3 (DR3) [17, hereafter Z06]. In 2013, a new catalogue of 19 712 spectroscopically confirmed WDs was released, based on the SDSS DR7 [18, hereafter K13]. This catalogue consisted mainly of single WDs, but also included WDs with binary companions.

To date, the Z06 and K13 catalogues are the largest and most recent spectroscopically confirmed samples of NLS1s and WDs respectively. These samples were subsequently utilized as "training sets". For each training set, a cross-correlation with the AllWISE catalogue [19] was performed with the CDS XMatch Service[1], using a search radius of 2 arcsec. It was found that 2006 of the 2011 Z06 NLS1s have AllWISE counterparts (i.e. 99.8%), while only 3022 of the 19 712 K13 WDs have AllWISE counterparts (15.3%).

The AllWISE catalogue contains not only the WISE $W1$, $W2$, $W3$ and $W4$ magnitudes, but also the 2MASS J, H and K magnitudes, for those cases where the source was also observed and detected with 2MASS. Various different combinations of colour-colour and colour-magnitude plots were calculated for the Z06 and K13 samples, and it was found that they are quite well separated on 4 of these plots: $K - W1$ vs. $H - K$; $K - W1$ vs. $W1$; $W1 - W2$ vs. $K - W1$ and $W1 - W2$ vs. $W1$ (figure 1). Only actual detections in each filter were used for these plots: if only upper limits were available, the source was not included. The colours of the Z06 NLS1s agree very well with the known colours of broad-line AGN candidates in general [16].

Each of the 8 scatter plots in figure 1 were subsequently converted to a continuous map, for easier visualization, and especially to enable the assignment of a numerical value to each ss2RXS candidate based on its position on these maps, as described in §3.2. Each map was created by including each source (i.e. each data point) as a normalized two-dimensional gaussian with its RMS width in each dimension equal to the error of the data point in that particular dimension, over the full relevant colour-colour or colour-magnitude parameter space. The map was then divided by the peak height of the distribution, to yield a "normalized" map where the value at a certain colour-colour or colour-magnitude combination represents the distribution's "peak height fraction" (PHF) for that combination. This PHF is not an actual probability, but does provide a comparative numerical value with which to assess the relative chance of an unknown object belonging to either the NLS1 or WD class.

[1] http://cdsxmatch.u-strasbg.fr/xmatch

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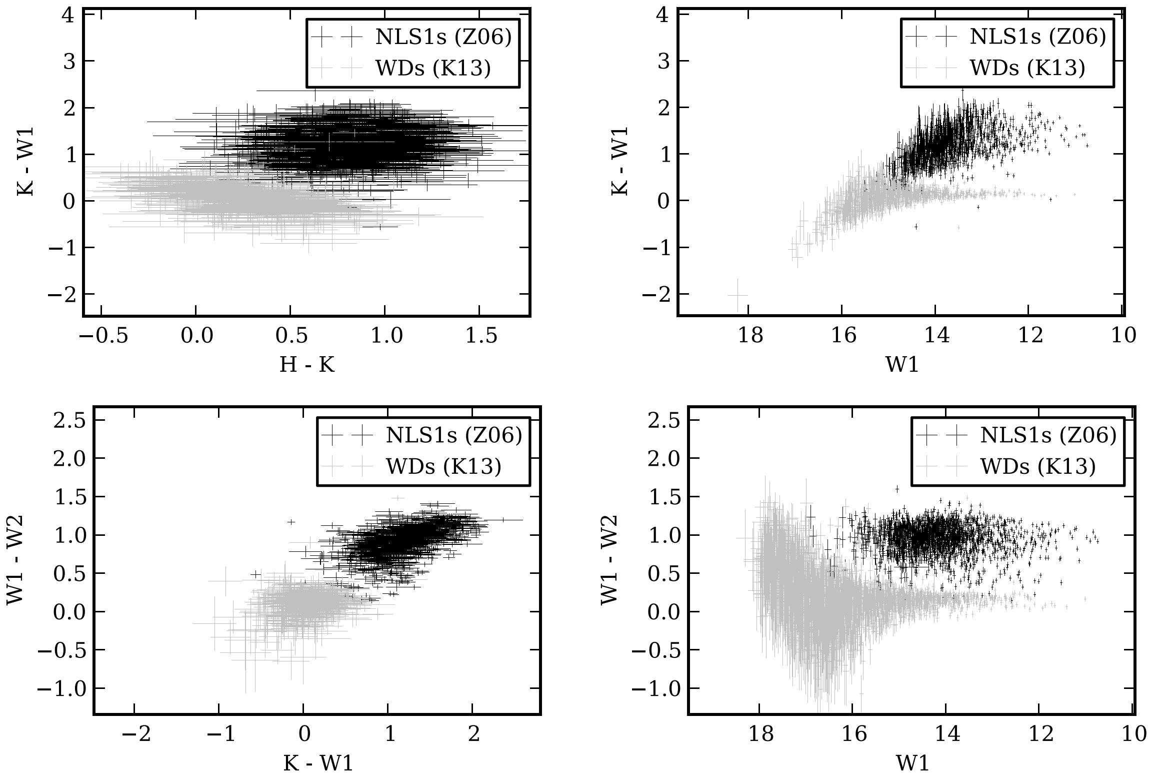

Figure 1. AllWISE colour-colour and colour-magnitude plots for the Z06 and K13 training samples. Note how each sample plots on a well defined region on each diagram, and how the two samples can be separated from each other quite well. Each data point represents one source.

3.2. Using AllWISE colours to distinguish NLS1s from WDs in the ss2RXS sample

One of the challenges in the identification of 2RXS sources with detections from other catalogues, is the relatively large positional error circle: the 1-sigma positional error for the ss2RXS sample is ∼7 arcsec on average, but varies up to ∼50 arcsec. Within this error circle, there are often several possible counterparts in e.g. the optical and infrared. Consequently, the AllWISE catalogue was queried for every ss2RXS source, and each AllWISE detection within a 5-sigma error radius around that source was stored in the ss2RXS database.

For each potential AllWISE counterpart, its detected magnitudes were used to calculate a mean $NLS1_{PHF}$ and mean WD_{PHF} associated with its position on the NLS1 and WD continuous maps respectively. It was mentioned previously that 99.8% of the Z06 NLS1s were detected by AllWISE. Among these, the source was detected without exception in both the $W1$ and $W2$ bands, and in the vast majority of cases in the $W3$ and $W4$ bands as well. This is to be expected, since AGN have significant emission over almost the whole electromagnetic spectrum. Therefore, one can expect that, for ∼99.8% of NLS1s, the position of the source can be located on at least the $W1 - W2$ vs. $W1$ map, implying that a value for $NLS1_{PHF}$ can indeed be determined.

On the other hand, only 15.3% of the K13 WDs were detected with AllWISE. Among this 15.3%, every single one was detected in $W1$, but some not in $W2$, and most of them not in $W3$ and $W4$. This implies that most WDs will not be detected by AllWISE, and for some of those detected, the calculation of a WD_{PHF} value might not be possible. However, this does yield the very useful conclusion that, if an infrared source with an $NLS1_{PHF}$ indicating NLS1 membership is not present near a certain ss2RXS source, that ss2RXS source is highly unlikely to be an NLS1, and belongs to a different class, possibly being a WD.

4. The nature of the ss2RXS sample: preliminary results

In addition to the cross-match with AllWISE described in the previous section, all potential counterparts within a 5-sigma positional error circle of each ss2RXS source were extracted from the following catalogues, and stored in the ss2RXS database: the *XMM-Newton* Serendipitous Source Catalogue, 3XMM-DR4 [20], the *XMM-Newton* slew survey catalogue, XMMSL1 [21], the *Chandra* Source Catalog, Release 1.1 [22], the 1SXPS *Swift* X-ray telescope point source catalogue [23], the Second ROSAT PSPC Catalog[2], the ROSAT HRI Pointed Observations[3], the CDS Simbad Astronomical Database [24], the catalogue of Quasars and Active Galactic Nuclei [25], the updated catalogue of Spectroscopically Identified White Dwarfs of McCook+ (2008) [26], the SDSS DR7 WD catalogue (K13), and also the SDSS DR3 NLS1 catalogue (Z06).

The following procedure was then carried out for each of the 1025 sources in the ss2RXS sample: The 2RXS position, as well as all the potential counterparts from the different catalogues, together with their associated error circles, were overplotted in the Aladin Sky Atlas [27]. Firstly, the positions of any detections with other X-ray missions were considered, since the (mostly) more accurate X-ray positions from the *XMM-Newton*, *Chandra* and *Swift* catalogues enable a more accurate identification of the correct optical/infrared counterpart.

Then, together with the other X-ray detections, the positions and properties of the nearby entries from all the other catalogues mentioned above were scrutinized, with special consideration of the $NLS1_{PHF}$ and WD_{PHF} values of the nearby AllWISE counterparts, and a series of judgements were made for the source. If a specific counterpart for the ss2RXS source could be identified from a certain catalogue with a high degree of certainty, a flag was set in the ss2RXS database indicating this counterpart. Flags were also set to indicate whether the ss2RXS source is already known as a NLS1, a WD, or a different type. For the unidentified sources, the available information was used to perform a pre-classification as being most likely a NLS1, WD or neither.

It was found that 40 sources in the ss2RXS sample are already listed as NLS1s in the Z06 catalogue, while 83 are already known as WDs. There are 370 sources with confirmed classifications as other source types, the vast majority of which are known stars with very bright optical and infrared magnitudes, the latter being brighter than 9 magnitudes in the $W1$ filter (clearly outside of the NLS1 and WD regions in figure 1). However, although these bright stars make out a substantial fraction of the total ss2RXS sample, we consider it unlikely that a significant amount of the remaining unidentified sample consist of bright stars, since (i) stars with these magnitudes are mostly well documented already, and (ii) the unidentified ss2RXS sources were not observed to coincide with such bright optical and infrared objects.

Among the remaining 532 sources, a further 370 are not in the Z06 NLS1 catalogue, but are highly likely to be NLS1s. Among these, 182 are already known in general as Seyfert 1s. Another 91 sources are considered likely to be new WD candidates. For the remaining 71 unidentified sources, insufficient information was available to perform a reliable prediction at this stage. As explained in §1, figure 8 of [8] shows that Seyfert 1s with $\Gamma \gtrsim 3$ are almost exclusively NLS1s. Even though BLS1s can be expected to have similar infrared colours to NLS1s (e.g. [16]), it is therefore very unlikely that the ss2RXS sample contains BLS1s, and the vast majority of the 182 known Seyfert 1s mentioned here can be considered to be NLS1s.

The estimates obtained from this preliminary analysis provide a basis from which to perform follow-up studies of the 370 new NLS1 candidates, and 91 new WD candidates. Although correlations with several large catalogues have been performed, a detailed literature study of these 461 candidates will be performed to discern whether a few of them might already have been identified elsewhere. Where necessary, spectroscopic follow-up studies with SALT (the Southern African Large Telescope) and the 1.9-m telescope at the SAAO (South African Astronomical Observatory) are planned to confirm the pre-classification, and to investigate the new source

[2] `http://cdsarc.u-strasbg.fr/viz-bin/Cat?IX/30`

[3] `http://cdsarc.u-strasbg.fr/viz-bin/Cat?IX/28A`

properties. The new NLS1s thus identified will be investigated by studying available multi-wavelength data, in combination with the spectral and variability information available in 2RXS, to further constrain the properties of this fascinating class. For those sources where a large 2RXS positional error circle and no other X-ray detections made counterpart identification impossible, follow-up pointings with *XMM-Newton* are planned to obtain more accurate X-ray positions.

5. Conclusion

A sample of 1025 sources with very soft X-ray spectra (the ss2RXS sample) were selected from the 2RXS catalogue. This sample was expected to contain a significant number of new NLS1 and WD candidates. By means of a rigorous analysis of the AllWISE detections of confirmed NLS1s and WDs, it has been shown that NLS1s can be successfully distinguished from WDs (and also very bright stars) on the basis of infrared colours and magnitudes. By visually screening each of the 1025 sources individually, utilizing the infrared selection method, as well as cross-correlations with other catalogues, it was found that there are potentially 370 new NLS1 candidates, and 91 new WD candidates, within the ss2RXS sample. This initial analysis and pre-classification provides a starting point for further follow-up studies of the unidentified soft 2RXS sources.

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References

[1] Ghisellini G 2013 *Radiative Processes in High Energy Astrophysics* (*Lecture Notes in Physics* vol 873) (Heidelberg: Springer)
[2] Komossa S 2008 *Revista Mexicana de Astronomía y Astrofísica* (*Serie de Conferencias* vol 32) ed Benítez E *et al.* pp 86–92
[3] Osterbrock D E and Pogge R W 1985 *ApJ* **297** 166–176
[4] Goodrich R W 1989 *ApJ* **342** 224–234
[5] Véron-Cetty M P, Véron P and Gonçalves A C 2001 *A&A* **372** 730–754
[6] Seward F D and Charles P A 2010 *Exploring the X-ray Universe* (New York: Cambridge University Press)
[7] Ishibashi W and Courvoisier T J L 2010 *A&A* **512** A58
[8] Boller T, Brandt W N and Fink H 1996 *A&A* **305** 53–73
[9] Mathur S, Kuraszkiewicz J and Czerny B 2001 *New Astronomy* **6** 321–329
[10] Peterson B M *et al.* 2000 *ApJ* **542** 161–174
[11] Boroson T A and Green R F 1992 *ApJS* **80** 109–135
[12] Fleming T A, Snowden S L, Pfeffermann E, Briel U and Greiner J 1996 *A&A* **316** 147–154
[13] Boller T, Freyberg M J, Trümper J, Haberl F, Voges W and Nandra K 2016 *A&A* **588** A103
[14] Voges W *et al.* 1999 *A&A* **349** 389–405
[15] Voges W *et al.* 2000 *VizieR Online Data Catalog* **9029**
[16] Edelson R and Malkan M 2012 *ApJ* **751** 52
[17] Zhou H, Wang T, Yuan W, Lu H, Dong X, Wang J and Lu Y 2006 *ApJS* **166** 128–153
[18] Kleinman S J *et al.* 2013 *ApJS* **204** 5
[19] Cutri R M *et al.* 2014 *VizieR Online Data Catalog* **2328**
[20] XMM-Newton Survey Science Centre C 2013 *VizieR Online Data Catalog* **9044**
[21] Saxton R D, Read A M, Esquej P, Freyberg M J, Altieri B and Bermejo D 2008 *A&A* **480** 611–622
[22] Evans I N *et al.* 2010 *ApJS* **189** 37-82
[23] Evans P A *et al.* 2013 *VizieR Online Data Catalog* **9043**
[24] Wenger M *et al.* 2000 *A&AS* **143** 9–22
[25] Véron-Cetty M P and Véron P 2010 *A&A* **518** A10
[26] McCook G P and Sion E M 1999 *ApJS* **121** 1–130
[27] Bonnarel F, Fernique P, Bienaymé O, Egret D, Genova F, Louys M, Ochsenbein F, Wenger M and Bartlett J G 2000 *A&AS* **143** 33–40