The first look at narrow-line Seyfert 1 galaxies with eROSITA

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ABSTRACT

We present the first look at the spectral and timing analysis of narrow-line Seyfert 1 galaxies (NLS1s) with the extended ROentgen Survey with an Imaging Telescope Array (eROSITA) on board the Spectrum-Roentgen-Gamma (SRG) mission. The sample of approximately 1200 NLS1s was obtained via a cross-match between the first eROSITA All-Sky Survey (eRASS1) catalogue and the catalogue of spectroscopically selected NLS1s from the twelfth data release of the Sloan Digital Sky Survey (SDSS) DR12. The X-ray spectral analysis is based on a simple power-law fit. The photon index distribution has a mean value of about 2.8 ± 0.03, as expected from previous X-ray studies of NLS1s. Interestingly, it is positively skewed, and about 10\% of the sources are located in the super-soft tail of photon indices larger than 4. These sources are of further interest as their source counts run into the X-ray background at values at around 1 keV. We argue that ionised outflows have been detected by eROSITA and may account for some of the extreme spectral steepness, which is supported by correlations found between the photon index and optical outflow parameters. We analysed the intrinsic X-ray variability of the eRASS1 to eRASS3 light curves of the sample but do not find significant variability either during the individual survey scans or between them.

Key words. X-rays: general – surveys – galaxies: Seyfert – Accretion, accretion discs

1. Introduction

The mass of the supermassive black hole at the centre of a galaxy is known to be strongly correlated with the stellar velocity dispersion, which is believed to be a consequence of the feeding and feedback working together to self-regulate the black hole growth and galaxy evolution (Kormendy & Ho 2013). While the feeding mechanism provides a vast amount of gas supply to the supermassive black hole, helping the active galactic nucleus (AGN) to grow, the strong radiation from the AGN quenches the gas supply and halts the growth of the supermassive black hole, thereby regulating its growth and, with that, galaxy evolution (see King & Pounds 2015). The gas outflow, which is considered a tracer of feedback from AGN, has been reported at various wavelength bands, namely optical, UV, and X-ray (e.g. Reeves et al. 2003; Arav et al. 2013), allowing us to study feedback at different spatial scales. For example, kiloparsec (kpc) outflow as traced by the asymmetry and velocity shift of the [O III] $\lambda 5007$ (e.g. Rakshit & Woo 2018) allows us to investigate the interaction of outflow with the interstellar medium, while the small-scale outflow as seen in the X-ray band could help us to study the wind from the accretion disc (e.g. Crenshaw et al. 2003; Reeves et al. 2009; Tombesi et al. 2015). These previous studies suggest strong correlations between [O III] $\lambda 5007$ velocity shift and dispersion with the accretion rate of AGN, suggesting the gas outflow is driven by the accretion rate (Rakshit & Woo 2018). Particularly for objects with high accretion rates, AGN feedback processes are thought to be of importance. Outflowing winds launched from the accretion disc by radiation pressure or magnetic fields are considered an important AGN feedback process. For radiation-pressure-dominated winds, outflows can reach velocities of up to about 0.3\,c and can drive substantial amounts of material into the interstellar medium. These winds have mostly been discovered based on XMM-Newton observations (e.g. Pounds et al. 2003a,b,c; King & Pounds 2003; Reeves et al. 2003). Outflowing winds with such high velocities have been named ultra-fast outflows (UFOs) by Tombesi et al. (2010) in a systematic study of bright XMM-Newton AGN. Reviews on AGN outflows in general have been presented by Fabian (2012) and Parker et al. (2021), among others.

Narrow-line Seyfert 1 galaxies (NLS1s) are a subclass of AGN with high Eddington rates and are defined by the relative narrowness of their broad emission lines – with the full width at half maximum (FWHM) of the broad H$\beta$ line being less than ~2000 km s$^{-1}$, a ratio of the [OIII] to H$\beta$ line flux of less than 3, and strong Fe II multiplet emission (Osterbrock & Pogge 1985; Goodrich 1989). NLS1s are thought to be AGN with low black hole masses in their early phase of accretion (e.g. Boller et al. 1996). Due to their high Eddington rates and strong outflows, NLS1s are ideally suited for the study of accretion physics in the strong General Relativity (GR) regime in the innermost regions of AGN, and relativistic effects are expected to be prominent features of eROSITA (Merloni et al. 2012; Predelli et al. 2021) observations. Therefore, eROSITA observations are expected to advance our understanding of matter under strong gravity, and determining the NLS1 content in the eROSITA data will build advance our understanding of matter under strong gravity, and
eROSITA, developed by the Max Planck Institute for Extraterrestrial Physics (MPE) and launched in 2019, provides the first all-sky survey in the complete 0.2–8 keV band with better energy resolution than ROSAT and comparable sensitivity in the soft X-rays to that of XMM-Newton. In this paper, we present the first population study on a large homogeneous sample of approximately 1200 spectroscopically confirmed NLS1s using eROSITA data, marking a 25-fold increase in sensitivity and much improved spectral resolution in the soft X-ray compared to the ROSAT survey data used in previous studies (e.g. Anderson et al. 2007; Rakshit & Woo 2018). The unique soft-X-ray energy response of eROSITA allows novel studies of the soft-X-ray spectral energy distribution (SED) on the largest sample of spectroscopically confirmed NLS1s to date, and provides an opportunity to study outflow signatures from the gravitational radius scale to kpc-scale.

The structure of the paper is as follows. We describe our sample selection in Sect. 2, and present our X-ray spectral analysis in Sect. 3. The optical line asymmetry and outflow indicator parameter determination are outlined in Sect. 5. We present the results of this paper in Sect. 6, the variability results in Sect. 7, and a discussion in Sect. 8. We summarise our results in Sect. 9.

2. DR12 NLS1 cross-match with eRASS1

The main operational phase of eROSITA is the eight-fold all-sky survey, labelled eRASS1–8. A simple positional cross-match of eRASS1 X-ray counterparts using astrometrically corrected positions to the optical coordinates of the Sloan Digital Sky Survey (SDSS) DR12 catalog of Rakshit et al. (2017) within 12 arcsec yielded 2238 matched sources.

The source products were obtained by the eROSITA Science Analysis Software System (eSASS) configuration which is designed for eRASS1 data analysis and source products and corresponding data release (Merloni & Consortium, in prep.). Sources for which less than ten net photon counts were detected were rejected from the spectral fitting analysis due to an expected insufficient signal-to-noise ratio (S/N), leaving 1374 sources. Of these, spectral files produced by the eSASS pipeline were available for 1197 sources. We note that the combined positional uncertainty of the eRASS1 and the DR12 surveys peaks at around 6 arcsec. When cross-matching DR12 NLS1 objects to eRASS1 counterparts we used a maximum positional separation of 12 arcsec. We also note that the projected proximity of two detections does not automatically mean the sources are identical. More sophisticated cross-matching algorithms are available that take into account magnitudes, colours, and other additional information, such as NWAY (e.g. Salvato et al. 2018). In this case, the assignment of the counterparts by NWAY compared to the simple positional cross-match differed only marginally.

The $AL_{5100}$ versus redshift distribution of DR12 – eRASS1 NLS1 and the distribution of X-ray counts are shown in Fig. 1.

3. X-ray spectral analysis

PyXspec, a Python interface for the XSPEC (Arnaud 1996) spectral-fitting program, was used for automated maximum-likelihood-based fitting using the Cash statistics, the modified Levenberg-Marquardt algorithm, and a principal component analysis (PCA)-based automated background modelling tool implemented in the Bayesian X-ray analysis (BXA) software package (Buchner et al. 2014) as described in Simmonds et al. (2018). This fitting provided the spectral properties of the eRASS1 NLS1 cross-matched sample as described in Grünwald (2022).

We tested a combined black body and power-law model to account for the soft-X-ray excess emission from the disc and the coronal emission, respectively. Due to the relatively low photon count statistic resulting from the short exposure times, the parameter spaces appeared to be very inhomogeneous and featured multiple local minima most of which were not physically meaningful parameter ranges. Some of these minima were not physically plausible, and such fits were deemed unreliable (Grünwald 2022).

Instead, we adopted a simple power-law model ($zpowerlw$ in XSPEC) with foreground absorption (TBabs with the Verner et al. 1996 photoionisation cross sections and the Wilms et al. 2000 abundances). The corresponding equivalent hydrogen column density (in units of $10^{21}$ atoms cm$^{-2}$) $N_H$ was initially kept as a free parameter; only when $N_H$ could not be fitted was it fixed to the Galactic value$^1$ in the direction of the source, $N_{H,gal}$.

The photon index distribution obtained from the power-law fit is shown in Fig. 2. The mean photon index and the standard error of the mean are 2.81 ± 0.03. This is steeper compared to other AGN samples obtained with eROSITA (e.g. Liu et al. 2022), as expected for NLS1s. We note that about 10% of the distribution has photon indices above 4, reaching values up to about 10. This super-soft tail has not been detected to such an extent in previous X-ray NLS1 studies.

To account for the known degeneracy between photon index and $N_H$ for low-count spectra, we fixed $N_H$ to the Galactic value for all sources. The resulting distribution has a slightly lower mean photon index with 2.59 ± 0.02, but still reaches values above 5 (Fig. 3). The mean values, errors, and standard deviations of $\Gamma$ for the different treatments of $N_H$ as shown in Figs. 2 and 3 are listed in Table 1.

Figure 4 shows the average unfolded spectrum for objects with $\Gamma \geq 4$, $4 > \Gamma \geq 2$, and $2 > \Gamma$, respectively, as determined by fitting the power-law component only. For the corresponding distribution of the photon index, see Fig. 3. The observed spectra were unfolded using the XSPECs uXspec command and the respective best-fitting parameters of the power-law model, and the stacking within each steepness group was done by taking the arithmetic mean of the unfolded data following the approach by Liu et al. (2016).

$^1$ The galactic column was obtained from https://www.swift.ac.uk/analysis/nhtot/index.php
4. Partial covering by an outflowing ionised absorber

Grünwald (2022) showed that ionised outflowing winds can explain photon indices with values above 5. As opposed to a cold (neutral) absorber, a warm absorbing material where lighter elements are ionised will be transparent to soft X-rays while still being opaque to higher energies. At the same time, an ionised absorber will imprint a prominent absorption feature composed of lines from moderately ionised Fe, Ne, and Mg. This causes a loss of photons beyond the soft band, manifesting as a steeper photon index distribution of the sample. A photon index of 2.5 is reached when freezing $N_{\text{H}}$ as a free parameter was successful. For the latter subsample, the distribution is shifted to slightly higher photon indices. The solid vertical line mark the mean at 2.6 ($N_{\text{H}}$ fixed) and 3.9 ($N_{\text{H}}$ free). Some increase in steepness is realistic due to the degeneracy as $N_{\text{H}}$ (fixed) gives a lower bound to the true value of $N_{\text{H}}$. The dotted vertical line is the typical slope of X-ray-emitting AGN in the eFEDS field, as shown by Liu et al. (2022).

Table 1. Mean value, standard error of the mean, and standard deviation of $\Gamma$ for the discussed treatments of $N_{\text{H}}$.  

| Statistic of $\Gamma$ | Mean | Sem. | Std. |
|-----------------------|------|------|------|
| Fixed                 | 2.59 | 0.02 | 0.71 |
| Free                  | 3.91 | 0.08 | 1.21 |
| Mixed, best-fit value | 2.81 | 0.03 | 1.00 |
| Mixed, best-fit value, counts 50 | 2.99 | 0.05 | 0.72 |
| Mixed, 90% confidence lower bound | 1.94 | 0.02 | 0.84 |

5. Optical spectral analysis

In order to estimate the line asymmetry and the outflow indicators such as velocity shift and dispersion of [OIII] line, we carefully fitted all the spectra to estimate various properties that are not available in the catalogue given in Rakshit et al. (2017). The ionisation parameter $\xi$ is defined as $\xi = \frac{L}{nr}$, where $L$ is the ionisation luminosity, $n$ is the gas density, and $r$ is the distance between the source and the absorber. When keeping the initial value for $N_{\text{H}}$, the photon index is increased to $\Gamma = 6.9$, compared to the initial value of $\Gamma = 4.5$. The absorber is blueshifted towards the observer with $z = -0.2$, corresponding to an outflow velocity of $\sim 0.4$ c. Fitting the data simulated for this scenario from 0.3 to 1.5 keV with a power law, while setting $N_{\text{H}} = 0.1 \times 10^{22}$ as suggested by the best fits of the steep objects of the sample, a photon index of $\Gamma = 7.4$ is reached, which further increases when assuming even higher outflow velocities.
For this purpose, we used the publicly available code PY-SOFIT developed by Guo et al. (2018). A detailed description of the code and the spectral fitting method used in the paper can be found in Rakshit et al. (2020). We corrected each spectrum for Galactic extinction using the Schlegel et al. (1998) map and extinction law from Fitzpatrick (1999) for the Milky Way with $R_v = 3.1$.

We de-redshifted each spectrum using the SDSS redshift and then performed detailed modelling of each spectrum. In short, we first decomposed stellar light using the PCA method from each spectrum using 5 PCA components for galaxies and 20 PCA components for quasars, which can reproduce about 98% of the galaxy sample and 96% of the quasar sample, respectively (Yip et al. 2004). We then subtracted the stellar contribution and modelled the AGN continuum, masking strong emission lines, as a combination of power law for the AGN contribution and Fe II emission using the optical Fe II template from Boroson & Green (1992) and the UV Fe II template from the UV template built by Shen et al. (2019).

To get the pure emission line spectrum and model the emission lines, we subtracted the best-fit continuum model from the spectrum and then performed multi-component modelling in individual line complexes. The broad emission lines ($\text{H}\beta$ and $\text{H}\alpha$) were modelled as a combination of broad components using two Gaussians, each with $\text{FWHM} > 900 \, \text{km s}^{-1}$ and a narrow component using a single Gaussian of $\text{FWHM} < 900 \, \text{km s}^{-1}$. We modelled the narrow lines using a single Gaussian of $\text{FWHM} < 900 \, \text{km s}^{-1}$ except the $[\text{O III}\lambda 5007]$ which we modelled using two Gaussians, one for the wing and one for the core components. During the fitting, the following restriction was applied, $F(5007)/F(4959) = 3$, $F(6585)/F(6549) = 3$, and the velocity shift and width of the narrow lines in a given complex were tied to each other. An example of a spectral fitting along with the decomposed components is shown in Fig. 6.

We estimated the uncertainty in each derived quantity via Markov chain Monte Carlo (MCMC) adding Gaussian noise based on the flux uncertainty to each spectrum and repeating this for 50 iterations. From the distribution of each quantity, we estimated 1$\sigma$ uncertainties on both sides (covering 16% and 84% of the sample) around the median.

Along with emission line width and flux of several emission lines, we also estimated the asymmetry index (AI) to characterise the shape of the emission lines using the method described in Heckman et al. (1981), Marziani et al. (1996), and Wolf et al. (2020). We used 75% and 25% flux values for the calculation of AI using the following equation:

$$
\text{AI} = \frac{\lambda_{\text{red}} + \lambda_{\text{blue}} - 2\lambda_{\text{peak}}}{\lambda_{\text{red}} - \lambda_{\text{blue}}},
$$

where $\lambda_{\text{peak}}$ is the wavelength corresponding to the peak flux, and $\lambda_{\text{red}}$ and $\lambda_{\text{blue}}$ are the wavelengths corresponding to the red and blue wings where the flux reaches 25% of the peak flux. For broad Balmer lines, we used only the broad component, and for $[\text{O III}\lambda 5007]$ we used the total profile to calculate the AI.

The line profile of $[\text{O III}\lambda 5007]$ has been used in the literature to study kpc-scale outflows; see for example Woo et al. (2018) and Rakshit & Woo (2018). The $[\text{O III}\lambda 5007]$ kinematics are mostly driven by non-gravitational components due to outflow, although the virial motion due to the gravitational potential adds to the line broadening.

The velocity dispersion ($\sigma_{\text{line}}$) and shift of the $[\text{O III}\lambda 5007]$ line are useful indicators of the outflow and can be estimated as

$$
\sigma_{\text{line}}^2 = \frac{\int \lambda^2 f_\lambda d\lambda}{\int f_\lambda d\lambda} - \lambda_{\text{avg}}^2,
$$

where $\lambda_{\text{avg}}$ is the wavelength corresponding to the peak flux and $f_\lambda$ is the flux density.
where

\[ \lambda_{\text{avg}} = \frac{\int f_\lambda d\lambda}{\int f_\lambda d\lambda} \]  

(3)

We calculated the velocity shift of [O III \( \lambda 5007 \)] (V[O III]) with respect to systemic velocity, which could be measured with respect to the shift of the Hβ narrow component (Rakshit & Woo (2018)). In order to reliably estimate the above quantities, a strong [O III \( \lambda 5007 \)] line is required. We therefore restricted further analysis with S/N at [O III \( \lambda 5007 \)] larger than 5 and Hβ broad component detected at 5σ. This restricts us to a sample of 723 objects for the further analysis presented in the following section.

6. Results

6.1. Dependency of photon index with AGN parameters

To study the dependency of photon index with the physical parameters of AGN, we calculated black hole mass based on the virial relation:

\[ M_{\text{BH}} = f R_{\text{BLR}} \Delta V^2 / G, \]  

(4)

where \( R_{\text{BLR}} \) is the size of the broad line region (BLR) estimated using the BLR size–luminosity relation from Bentz et al. (2013). \( \Delta V^2 \) is the line FWHM and \( f \) is the virial scale factor which is taken to be 1.12 from Woo et al. (2015). We also estimated the Eddington ratio (\( R_{\text{Edd}} \)), which is the ratio of bolometric (\( L_{\text{bol}} \)) to Eddington (\( L_{\text{Edd}} \)) luminosity, where the bolometric luminosity is estimated as \( L_{\text{bol}} = 9 \times L_{5100} \) and \( L_{\text{Edd}} \) is estimated as \( L_{\text{Edd}} = 1.26 \times 10^{38} M_{\text{BH}} \).

Boroson & Green (1992) studied 87 PG quasars and introduced the AGN Eigenvector-1 (E1) space, which can explain diverse properties of broad-lined AGN. The E1 space has been extended in different wavelength bands and the current E1 space is dominated by three parameters: photon index in soft X-ray, R4570, and the FWHM of the line.

Figure 7 shows the correlations between the photon index against \( L_{5100} \), Fe II strength (R4570) – which is the flux ratio of Fe II (4435–4685 Å) to Hβ broad component –, \( M_{\text{BH}} \), and \( R_{\text{Edd}} \). The Spearman’s rank correlation parameters and \( p \)-value of no correlation are listed in Table 2. We also performed linear fits to the correlation between \( \Gamma \) and various parameters using LINMIX code⁴ (Kelly 2007) with intrinsic random scatter (\( \epsilon \)) about the regression (here \( \epsilon \) is assumed to be normally distributed with zero mean and variance \( \sigma^2_{\text{intrinsic}} \)). The results are shown in Table 3.

The strongest correlation between these parameters is the positive correlation between photon index \( \Gamma \) and \( R_{\text{Edd}} \), which agrees well with findings in the literature. For example, Ojha et al. (2020) found a strong negative correlation between NLS1 parameters considering the soft-X-ray photon index of an NLS1 sample. This correlation is also present in the total sample of NLS1 (221 objects) and the broad-line Seyfert 1 galaxies (BLS1; 154 objects) sample based on ROSAT and XMM-Newton spectral fitting. Wang et al. (2016) studied the correlation between the hard-X-ray (2–10 keV) photon index and various physical parameters, and found a strong positive correlation between photon index and \( R_{\text{Edd}} \). Therefore, this correlation is not only valid for soft X-rays but also for the hard-X-ray photon index.

We note that \( R_{\text{Edd}} \) is \( \propto L_{5100} \) and is inverse to the Eddington luminosity or the black hole mass, which is again proportional to \( L_{5100} \) and the square of \( \Delta v \). We find a strong positive correlation between \( \Gamma \) and \( L_{5100} \) and no correlation between \( \Gamma \) and \( M_{\text{BH}} \). The latter is due to the combined effect of the \( \Gamma – L_{5100} \) correlation and the anti-correlation between \( \Gamma \) and \( \Delta v \), which was previously shown by various authors (e.g. Wang et al. 2016; Ojha et al. 2020), and is especially prominent for a sample with a large range of \( \Delta v \). The Fe II strength and Eddington ratio are known to be correlated, suggesting that a positive correlation between \( \Gamma \) and R4570 is expected, which is also found in our eRASS1 sample.

The correlation coefficient found in this large-sample eRASS1 study is lower than the one found in previous studies based on a much smaller sample. We note that our original sample considers all the objects with photon counts larger than 10⁶. Considering the sources with large photon counts could improve the correlation statistics. To test this, we performed the correlation at various photon count levels; for example >30 and >50. We find a much stronger correlation when objects with higher photon counts are considered (see values in parenthesis in Table 2 and the blue points in Fig. 7 for sources with photon count >50).

**Fig. 7.** Correlation of the photon index obtained for fixed \( N_\text{H} \) fit to SDSS DR12 sample properties (luminosity, Fe II strength, black hole mass, and Eddington ratio) for sources with photon counts larger than 10 (red-dot) and 50 (blue-square). The best-fit lines for both samples are shown.

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⁴ https://github.com/jmeyers314/linmix

⁵ Throughout the paper, we use sources with net photon counts of greater than 10 unless mentioned otherwise.
the correlation between λ at X-rays generated in the corona close to the black hole – as in fast infall. The strong blue asymmetry in the Hβ could drive these outflows to kpc-scales. Jha et al. (2021) found that the radiation pressure or wind from the accretion disc are found to be driven by the Eddington ratio, suggesting λ of a large number of Type 1 AGN using SDSS spectra and λ. Rakshit & Woo (2018) studied the [O III] λ 5007\textsc{iii} emission. The values in brackets are for photon counts of 50. Spearman correlation coefficient and p-value of no correlation are given for all the correlations.

### Table 2. Correlation results of photon index Γ with several parameters for fixed N_H (Cols. 4 and 5) and mixed N_H (Cols. 6 and 7).

| Col. | y | x         | r_s  | p-value | N_H fixed | r_s  | p-value |
|------|---|-----------|------|---------|-----------|------|---------|
| (1)  | (2) | (3)       | (4)  | (5)     |           | (6)  | (7)     |
| 1    | Γ  | log L_{5100} | 0.20 (0.53) | 5e–8 (1e–12) | 0.09 (0.38) | 8e–3 (1e–6) |
| 2    | Γ  | R_{4570}   | 0.10 (0.32) | 0.01 (1e–4) | 0.08 (0.36) | 0.02 (1e–5) |
| 3    | Γ  | log M_{BH} | 0.08 (0.26) | 0.02 (1e–3) | −0.01 (0.13) | 0.65 (0.09) |
| 4    | Γ  | log R_{Edd} | 0.28 (0.65) | 2e–15 (1e–19) | 0.22 (0.50) | 2e–9 (5e–11) |
| 5    | Γ  | σ(OIII) | −0.16 (–0.29) | 2e–3 (9e–3) | −0.14 (–0.26) | 8e–3 (0.02) |
| 6    | Γ  | AI (OIII)| 0.18 (0.46) | 4e–4 (1e–5) | 0.14 (0.40) | 8e–3 (2e–4) |
| 7    | Γ  | AI (Hβ) | −0.10 (–0.33) | 0.06 (3e–3) | −0.07 (–0.21) | 0.16 (0.06) |
| 8    | Γ  | AI (Hβ)| −0.11 (–0.34) | 0.02 (2e–3) | −0.08 (–0.30) | 0.11 (7e–3) |
| 9    | Γ  | v_{out} | 0.20 (0.48) | 2e–4 (6e–6) | 0.16 (0.42) | 2e–3 (1e–4) |
| 10   | Γ  | log M_{out} | 0.22 (0.46) | 1e–5 (2e–5) | 0.14 (0.34) | 6e–3 (2e–3) |
| 11   | Γ  | log E_{out} | 0.23 (0.53) | 5e–6 (3e–7) | 0.16 (0.41) | 1e–3 (1e–4) |
| 12   | Γ  | log P_{out} | 0.23 (0.51) | 7e–6 (1e–6) | 0.15 (0.40) | 3e–3 (3e–4) |
| 13   | log R_{Edd} | log M_{out} | 0.62 (0.68) | 6e–42 (5e–12) | 0.64 (0.68) | 2e–42 (1e–11) |
| 14   | log R_{Edd} | log E_{out} | 0.58 (0.67) | 7e–36 (2e–11) | 0.59 (0.67) | 4e–36 (3e–11) |
| 15   | log R_{Edd} | log P_{out} | 0.61 (0.69) | 4e–39 (3e–12) | 0.62 (0.68) | 2e–39 (6e–12) |

**Notes.** The values in brackets are for photon counts of 50. Spearman correlation coefficient and p-value of no correlation are given for all the correlations.

### Table 3. Best fit relation using LINMIX code for fixed N_H and photon counts larger than 10.

| Col. | y | x         | Slope | Intercept | σ^2_{out} |
|------|---|-----------|-------|-----------|-----------|
| (1)  | (2) | (3)       | (4)   | (5)       | (6)       |
| 1    | Γ  | log L_{5100} | 0.22 ± 0.04 (0.42 ± 0.06) | −7.22 ± 1.72 (−15.82 ± 2.47) | 0.14 ± 0.02 (0.1 ± 0.02) |
| 2    | Γ  | R_{4570}   | 0.20 ± 0.06 (0.35 ± 0.10) | 2.41 ± 0.05 (2.36 ± 0.09) | 0.15 ± 0.02 (0.14 ± 0.03) |
| 3    | Γ  | log M_{BH} | 0.13 ± 0.06 (0.37 ± 0.10) | 1.58 ± 0.43 (0.02 ± 0.75) | 0.16 ± 0.02 (0.14 ± 0.02) |
| 4    | Γ  | log R_{Edd} | 0.68 ± 0.08 (0.91 ± 0.10) | 2.89 ± 0.04 (3.13 ± 0.06) | 0.12 ± 0.02 (0.07 ± 0.02) |
| 6    | Γ  | v_{out}/1e−3 | 1.51 ± 0.34 (2.08 ± 0.55) | 2.20 ± 0.09 (2.14 ± 0.15) | 0.15 ± 0.02 (0.15 ± 0.04) |
| 7    | Γ  | AI (OIII)| −0.45 ± 0.21 (−0.91 ± 0.38) | 2.50 ± 0.05 (2.5 ± 0.09) | 0.16 ± 0.03 (0.18 ± 0.04) |
| 8    | Γ  | AI (Hβ) | −0.74 ± 0.32 (−1.75 ± 0.66) | 2.57 ± 0.03 (2.65 ± 0.05) | 0.17 ± 0.03 (0.17 ± 0.04) |

**Notes.** Column 2 is the y-variable, Col. 3 is the x-variable, Col. 4 is the slope, Col. 5 is the intercept, and Col. 6 is the variance of the intrinsic scatter.

counts larger than 50); however, this reduced the sample size significantly as shown in Fig. 1. Therefore, the correlations become weaker when sources with low photon counts are considered.

### 6.2. Correlation between outflow indicators and photon index

Rakshit & Woo (2018) studied the [O III] λ 5007\textsc{iii} kinematics of a large number of Type 1 AGN using SDSS spectra and found a kinematic signature of non-virial motion in the majority of the sources. The [O III] λ 5007\textsc{iii} velocity shift and dispersion are found to be driven by the Eddington ratio, suggesting that the radiation pressure or wind from the accretion disc could drive these outflows to kpc-scales. Jha et al. (2021) found strong blue asymmetry in the Hβ line, indicating strong outflows in NLS1s compared to the BLS1s, which are dominated by infall.

To investigate a possible link between the ionised outflows at X-rays generated in the corona close to the black hole – as traced by the soft-X-ray photon index – and the large-scale outflow that is seen in [O III] λ 5007\textsc{iii} and Hβ kinematics, we plotted the correlation between Γ and various outflow indicators; see Fig. 8. Here, we excluded objects with a low velocity shift of |V[OIII]| < 10 km s\(^{-1}\). In particular, we find that the majority of the sources show blueshifted (negative velocity) [O III] λ 5007\textsc{iii} lines with velocities in the range of −100 km s\(^{-1}\) to −300 km s\(^{-1}\). Additionally, those highly blueshifted objects also show larger velocity dispersion up to ∼400 km s\(^{-1}\). Indeed, the velocity-dispersion diagram (VVD) shown in the upper left panel of Fig. 8 shows clear outflow signatures where high photon indices have higher blueshifts and dispersion. We also plotted the outflow velocity which is represented as V_{out} = \sqrt{V[OIII]^2 + C_{OIII}^2}. We find V_{out} positively correlates with Γ. The asymmetry indices calculated from the [O III] λ 5007\textsc{iii} and broad Hβ model profile are shown in the bottom panel of Fig. 8. The majority of the objects have negative asymmetry in [O III] λ 5007\textsc{iii}, which is a signature of outflow. A similar trend is also seen in the case of Hβ asymmetry.

### 6.3. Outflow energetics

We calculated the energetics of the gas outflows, that is, mass accretion rate, energy injection, and power output, based on the simple bi-conical outflow and case B recombination (Crenshaw et al. 2010; Bae & Woo 2016; Rakshit & Woo 2018).
Using the \([\text{OIII}]\lambda5007\) luminosity, we first estimated the mass of the ionised gas following Nesvadba et al. (2011):

\[
M_{\text{gas}} = 0.4 \times 10^8 M_\odot \times (L_{\text{[OIII]}}/1000 \text{cm}^{-2}/n_e),
\]

where \(n_e\) is the electron density, which depends on several factors, such as gas temperature, ionisation mechanism, and geometry of the narrow-line region (NLR). We took the median value of \(n_e = 272\) from Rakshit & Woo (2018) and calculated the gas mass. We calculated the size of the gas outflow (\(R_{\text{out}}\)) based on the empirical relation based on the integral field spectroscopy by Kang & Woo (2018):

\[
\log R_{\text{out}}(\text{kpc}) = (0.28 \pm 0.03) \times \log L_{\text{[OIII]}} - (11.27 \pm 1.46),
\]

which ranges between 0.6 and 7.2 kpc with a median of 2 kpc. At the median radius, the mass outflow rate (\(M_{\text{out}}\)), energy injection rates (\(E_{\text{out}}\)), and momentum flux (\(P_{\text{out}}\)) can be calculated as

\[
M_{\text{out}} = 3 \times 10^7 M_\odot \frac{v_{\text{out}}}{R_{\text{out}}}, \quad E_{\text{out}} = \frac{1}{2} M_{\text{out}} v_{\text{out}}^2, \quad P_{\text{out}} = M_{\text{out}} v_{\text{out}}.
\]

Here, \(v_{\text{out}} = \sqrt{\langle \eta_{\text{OIII}} \rangle^2 + \sigma_{\text{[OIII]}}^2}\) is the outflow velocity.

In Fig. 9, we show the outflow energetics for the NLS1 in our sample as a function of photon index colour coded according to the Eddington ratio. The mass outflow rate ranges between 0.02 and 21 \(M_\odot \text{yr}^{-1}\) with a median at \(\sim 0.66 M_\odot \text{yr}^{-1}\); the energy injection rate is found to be \(6 \times 10^{36} - 6 \times 10^{37} \text{erg s}^{-1}\) with a median of \(1 \times 10^{36}\), and the momentum flux ranges between \(5 \times 10^{39}\) and \(4 \times 10^{34}\) dyne with a median of \(1 \times 10^{33}\) dyne. Rakshit & Woo (2018) calculated the outflow energetics for a large number of low-\(z\) type 1 AGN and found median values of \(M_{\text{out}}, E_{\text{out}}, P_{\text{out}}\) of \(0.48 M_\odot \text{yr}^{-1}, 1 \times 10^{40} \text{erg s}^{-1}, 8 \times 10^{32}\). Our measurements of outflow energetics of NLS1 are consistent with the values estimated for type 1 AGN.

Outflow energetics are found to be positively correlated with the photon index suggesting \(M_{\text{out}}, E_{\text{out}}, P_{\text{out}}\) are larger with steep spectra. Furthermore, the outflow energetics are positively correlated with the Eddington ratio. The plot further suggests that steep spectral sources are accreting at high Eddington rates and have larger mass outflow rates, energy injection, and momentum flux.

7. Timing analysis of the DR12 NLS1 content

We created light curves for all NLS1s detected in the first eROSITA all-sky survey scan (eRASS1). In addition, we compared these eRASS1 light curves with light curves detected in the second and third scans. We performed basic variability tests for the individual light curves. The survey data do not have sufficient exposure time to make definitive claims about variability, but some sources can be considered as variable candidates. We find 39 objects of the DR12 catalogue that match with eRASS1 and exhibit significance values of below 3\(\sigma\) for at least one of the three surveys. Table A.1 lists objects that show indications of X-ray variability. If one of the three surveys is not listed in the table, there is no sign of variability for this object in that survey. Only the surveys that show variability are presented.

8. Discussion

AGN outflows detected in the NLR and the potential connections to the feedback processes related to accretion physics have

Fig. 8. VVD diagram and correlation between photon index and outflow velocity (\(v_{\text{out}} = \sqrt{\langle \eta_{\text{OIII}} \rangle^2 + \sigma_{\text{[OIII]}}^2}\)) for fixed \(N_H\). The objects with zero velocity and zero AI of \([\text{OIII}]\lambda5007\) have been removed. **Bottom:** correlation of the photon index with outflow parameters for fixed \(N_H\) for sources with photon counts larger than 10 (red-dot) and 50 (blue-dot). The best-fit lines for both samples are shown.

Fig. 9. Mass outflow rate (top), energy injection rate (middle), and power output (bottom) are shown as a function of \(\Gamma\) with colour coding according to Eddington ratio for fixed \(N_H\) for sources with photon counts larger than 10 (red-dot) and 50 (blue-dot).
been proposed in several papers. Below, we discuss some previous basic findings and compare them to the eROSITA analysis presented in this paper.

8.1. Relations between the hard 2–10 keV photon index and the [O III] $\lambda$5007 line profile

A sample of 47 type 1 AGN extracted from the XMMi/SDSS-DR7 catalogue was analysed by Wang et al. (2016). The sample contains both NLS1s and BLS1s. These authors found a correlation between the [O III] $\lambda$5007 velocity shift and the velocity dispersion (their Fig. 7), and interpreted this relationship as wind- and/or radiation-driven outflow. The authors argue that the hard 2–10 keV photon index scales with the Eddington ratio which is interpreted as a moderate sign of general AGN outflows. It is argued that a cooled-down corona results in steeper hard photon indices. A general discussion on the accretion rate corona temperature relation is given in Boller et al. (2011). Interestingly, Fe K-edged absorption features of O VII ions at 0.74 keV (their Fig. 1) have been detected for 3 out of the 47 objects.

8.2. Gas outflows from large samples based on [O III] $\lambda$5007 kinematics

A recent analysis of a large sample of about 5000 type-1 AGN was performed by Rakshit & Woo (2018). The study is based on detailed outflow parameter determinations, including velocity shifts and velocity dispersions of the [O III] $\lambda$5007 line, and also both parameters in combination (VVD diagrams). The authors determined outflow energetics by calculating the mass outflow rate, the energy injection rate, and the momentum flux. These parameters were correlated with the bolometric luminosity and the relation to the accretion rates was derived. Based on the [O III] $\lambda$5007 velocity dispersion and VVD extending to higher values for higher luminosities and Eddington ratios, Rakshit & Woo (2018) concluded that radiation pressure or winds cause the outflow.

8.3. Soft X-ray studies and kpc-scale outflow studies before eROSITA

Jha et al. (2021) presented a study of 144 NLS1s and 117 BLS1s based on ROSAT and XMM-Newton observations. For their NLS1 sample, the fraction of objects showing outflow signatures as negative AI was three times higher than for the BLS1 sample. Figure 7 presented by these authors shows the correlation of outflow signatures with the photon index, Fe II strength, Eddington ratios, and nuclear luminosities. The correlations between these parameters have, in general, higher probability values than those of the analyses presented in this work, mainly because of the inclusion of BLS1 objects, which enlarges the parameter space.

8.4. Evidence for outflow from the gravitational radius up to the kpc-scale as seen by eROSITA

In this study, we used the asymmetry index and the soft-X-ray photon index for the first time to study AGN outflows based on eROSITA NLS1s DR12 detections. The superior soft-energy response of eROSITA allows us to perform unique studies of the relation between the X-ray spectral steepness in the soft-X-ray energy band and optical outflow indicators. In addition, this is the largest sample of NLS1s where the soft-X-ray photon is applied for outflow studies.

A connection between the accretion disc and the outflow in the NLR has been suggested by Wang et al. (2016) based on the hard 2–10 keV photon index. These authors argue that the hard-X-ray photon index is linked to the accretion process. In this scenario, the hard-X-ray photon index is produced by inverse Compton scattering of accretion disc photons in the hot ($>10^9$ K) corona.

In this paper, we use the soft-X-ray photon index from the eROSITA observations to study the launching mechanism driving AGN outflows. Ultra-fast ionised outflows with high covering fractions can potentially cause a moderately steep power law to appear extremely steep due to blueshifted absorption features of Fe L and lighter elements causing a depression of photons just above 1 keV. The observed photon index can then reach values well above five, as can be seen when simulating data using XSPEC’s zxipcf model. The eROSITA soft-X-ray photon index is therefore a better tracer of AGN outflows at the innermost gravitational radius scale compared to studies based on the hard X-ray photon index, which probes mainly Comptonisation effects.

The correlation between $\Gamma$ and Hβ asymmetry is weak but still present, and is stronger for photon counts above 50. We note that the geometry and kinematics of the BLR are highly complex. The low-ionisation broad line, such as Hβ, does not show any significant blueshift or redshift with respect to the systemic velocity on average which is evident from Fig. 8 as the majority of the objects have $\Delta$Hβ = 0 values compared to the high-ionisation lines, such as CIV, which are dominated by Keplerian motion. However, a high-quality reverberation mapping study shows the presence of inflow and outflow in Hβ of a few AGNs (e.g., Grier et al. 2017). Therefore, the presence of net radial motion and/or opacity effects could produce small Hβ asymmetry in some AGNs (Ercolino et al. 2012; Shen et al. 2016). We find strong correlations between the soft-X-ray photon index and the Eddington rate, the Fe II strength, and the [O III] $\lambda$5007 outflow velocity, dispersion, and the AI value.

The eROSITA studies, in combination with new asymmetry parameter calculations performed on the Rakshit et al. (2017) sample, provide strong evidence for the wind- and radiation-driven mode of AGN feedback processes in NLS1s.

9. Summary and outlook

We provide the first look at NLS1s based on the largest spectroscopically confirmed NLS1 sample obtained so far (Rakshit et al. 2017), which was obtained with the first X-ray all-sky survey scan of the eROSITA mission.

We adopted a single redshifted power-law model to model the entire spectrum. We also tested a combined black-body and power-law model to account for the soft-X-ray excess emission and the coronal emission, but the fits performed were deemed unreliable (Gruenwald 2022). The mean photon index is steep with about 2.8 as expected, but an ultra-soft photon index tail is found to skew the distribution to values as high as 10. This will be investigated further.

We extended the NLS1 sample of Rakshit et al. (2017) by re-fitting all spectra to determine the line asymmetry and outflow indicators. We determined the dependency of the photon index on AGN parameters, correlations between outflow indicators and the photon index, and the outflow energetics. We demonstrate that the eROSITA soft-X-ray photon index correlates with the parameters associated with large-scale [O III] and Hβ outflow. We argue that ionised outflows from the gravitational radius
scale up to the NLR region provide the best physical explanation for the eROSITA NLS1 SDSS DR12 data.

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Appendix A: Detailed investigation of the light-curve properties

We performed a standard normalised excess variance (NEV) and maximum amplitude variability (AMPL_MAX) analysis as described in Boller et al. (2022) for the light curves for eROSITA all-sky survey scan eRSS1, eRSS2, and eRSS3, respectively. In Table A.1 we list only those objects that have significance values in the standard variability tests of greater than zero.

Table A.1. Variable NLS1 source candidates of SDSS DR12.

| SDSS ID     | eRSS   | RA       | DEC       | AMPL_MAX | NEV  | Object Name                  | Detection | Redshift (spectroscopic) |
|-------------|--------|----------|-----------|----------|------|------------------------------|-----------|--------------------------|
| 0052-52024-0173 | 3 | 191.64687 | 2.36910 | 2.16 | 0.83 | LBQS 1244+028 | 2RXS, XMM | 0.04813 ± 0.00002 |
| 0052-52024-0173 | 2 | 191.64687 | 2.36910 | 2.16 | 1.23 | LBQS 1244+028 | 2RXS, XMM | 0.04813 ± 0.0002 |
| 0052-52040-0003 | 2 | 237.2003 | 11.68577 | 2.15 | 2.45 | 2MASS J11315615+0648583 | 2RXS | 0.12736 ± 0.0002 |
| 2265-53674-0046 | 3 | 19.7893 | 8.61620 | 2.00 | 5.46 | 2MASS J07591042+1151563 | 2RXS | 0.05014 ± 0.0003 |
| 2758-54948-0507 | 3 | 199.82842 | 24.52879 | 2.42 | 0.20 | LEDA 3096171 | 2RXS | 0.05014 ± 0.0003 |
| 0910-53577-0588 | 3 | 202.92096 | -1.87012 | 0.25 | 1.36 | 2MASS J13505681+0742344 | 2RXS | 0.17507 ± 0.0002 |
| 0331-52568-0552 | 2 | 180.6115 | -1.48757 | 0.34 | 0.20 | LEDA 90595 | 2RXS | 0.15080 ± 0.00015 |
| 0331-52568-0552 | 1 | 180.6115 | -1.48757 | 0.14 | 0.20 | LEDA 90595 | 2RXS | 0.15080 ± 0.00015 |
| 1805-53878-0402 | 3 | 207.73667 | 7.79056 | 0.30 | 0.20 | 2MASS J13505681+0742344 | 2RXS | 0.17507 ± 0.0002 |
| 2212-53579-0136 | 3 | 166.52686 | 25.59596 | 0.25 | 3.66 | 2MASS J11000689+2535454 | 2RXS | 0.07045 ± 0.0002 |
| 1829-53494-0249 | 2 | 207.6001 | 5.40646 | 0.20 | 0.20 | 2MASS J14424081+0524234 | 2RXS | 0.17103 ± 0.0004 |
| 0586-52023-0099 | 2 | 219.91786 | 3.09128 | 0.20 | 0.20 | 2MASS J14394028+0350283 | 2RXS | 0.26892 ± 0.00029 |
| 0585-52327-0386 | 3 | 216.95121 | 5.03946 | 0.20 | 0.20 | 2MASS J14274829+0302220 | 2RXS | 0.10589 ± 0.0002 |
| 2578-54993-0425 | 1 | 143.34329 | 13.94088 | 0.18 | 0.20 | 2MASS J02525237+1305388 | 2RXS | 0.07904 ± 0.0004 |
| 2370-53764-0123 | 1 | 147.51519 | 17.15908 | 0.17 | 0.20 | SDSS J095000.64+170932.6 | XMM-SUSAS1, XMM | 0.19497 ± 0.0002 |
| 0038-53278-0542 | 3 | 155.56169 | 5.66070 | 0.13 | 0.20 | 2MASS J11422485+0535386 | 2RXS | 0.10178 ± 0.0002 |
| 2067-53173-0034 | 3 | 182.93058 | 15.10774 | 0.12 | 0.20 | LEDA 1475434 | 2RXS | 0.07935 ± 0.0004 |
| 2007-53474-0294 | 3 | 161.77599 | 37.87385 | 0.10 | 0.20 | 2MASS J11070625+3752529 | 2RXS | 0.10193 ± 0.00016 |
| 0856-52339-0010 | 3 | 210.4062 | 8.32473 | 0.10 | 0.20 | LEDA 1475434 | 2RXS | 0.10193 ± 0.00016 |
| 0351-52506-0353 | 3 | 208.6476 | 2.87756 | 0.10 | 0.20 | 1RXS J135444.8+024122 | 2RXS | 0.13842 ± 0.0004 |
| 1233-52734-0185 | 3 | 189.45208 | 3.98878 | 0.06 | 0.20 | 2MASS J12374849+0323233 | 2RXS | 0.12444 ± 0.0004 |
| 2610-54476-0044 | 2 | 184.62852 | 18.85286 | 0.05 | 0.20 | 2MASS J12185308+1834582 | 2RXS | 0.19703 ± 0.00016 |
| 2507-53876-0253 | 2 | 174.73016 | 21.29640 | 0.05 | 0.20 | 2MASS J11385524+2117467 | 2RXS | 0.15608 ± 0.00016 |
| 0366-53637-0634 | 3 | 219.26718 | 0.11007 | 0.03 | 0.20 | 2MASS J11507516+2531484 | 2RXS | 0.08592 ± 0.0003 |

Notes. This table shows the variable NLS1 source candidates of SDSS DR12. The objects are sorted by decreasing AMPL_MAX values for a given SDSS ID (state-MID-fiber) value. If one of the three eROSITA surveys is not listed in this table for a particular object, there is no sign of variability for that object in this missing survey. The sources can be identified by their SDSS ID and coordinates. Additional detections are labelled as 2RXS (Boller et al. 2016), XMM (Webb et al. 2020), and XMM-SUSAS1 (Page et al. 2012), respectively. RA and DEC refer to the SDSS coordinates.