Probing the extremes of Seyfert activity: BeppoSAX observations of Narrow-Line Seyfert 1 galaxies

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Results are presented for the first year of observations of a selected sample of Narrow-Line Seyfert 1 galaxies (Ton S 180, RE J1034+396, Ark 564) obtained with the imaging instruments onboard BeppoSAX. These are the first simultaneous broad band (0.1–10 keV) spectra so far obtained for this class of objects.

1. INTRODUCTION

Narrow–line Seyfert 1 galaxies (NLS1) are defined by their optical emission line properties. They lie at the lower end of the broad line width distribution for the Seyfert 1 class with typical values of the H\(\beta\) FWHM in the range 500–2000 km s\(^{-1}\). The [O \textsc{iii}]/H\(\beta\) ratio is < 3, and strong Fe \textsc{ii} and high ionization iron lines are common among NLS1. They are characterized by unusually strong soft X-ray emission with very steep (\(\Gamma \simeq 3–5\)) spectral slopes in the ROSAT PSPC band \[\text{\textsuperscript{[1]}}\]. Large-amplitude and rapid X-ray variability is common among NLS1. The variability amplitude is significantly larger than that found in “normal” Seyfert galaxies \[\text{\textsuperscript{[2]}}\]. Moreover, there is evidence for giant-amplitude X-ray variability (up to about two orders of magnitude) in a few objects \[\text{\textsuperscript{[3]}}\]. It is notable that such extreme variability properties have been discovered, so far, only in NLS1. In the harder \(\approx 2–10\) keV energy band, recent ASCA observations have shown that NLS1 can have very different behaviour from classical broad-lined Seyfert 1s and quasars. A comparative ASCA study of a large sample of NLS1 and broad-line Seyfert 1s revealed that the \(\approx 2–10\) keV ASCA spectral slopes of NLS1 are generally steeper than those of broad line objects at a high statistical confidence level \[\text{\textsuperscript{[4]}}\].

The optical and X-ray properties of ultrasoft NLS1 have been discussed in detail by \[\text{\textsuperscript{[5]}}\] adopting a principal component analysis technique \[\text{\textsuperscript{[6]}}\]. The results indicate that they tend to lie at the ends of distributions of Seyfert quantities suggesting that they may have extremal values of some important physical parameter.

In order to increase the statistics of hard X-ray data for NLS1 galaxies and to better investigate their underlying physical processes we have undertaken a program of BeppoSAX observations of a sizeable sample of NLS1. We have selected, for the first year of observations, some of the brightest and most variable NLS1 previously observed by ROSAT and/or ASCA. The spectral capabilities of the detectors onboard BeppoSAX and especially the relatively large effective area at high energy (\(> 2\) keV) will allow a better study of the high energy properties of NLS1. In this paper we present the first simultaneous 0.1–10 keV spectral and variability properties for 3 objects, namely:

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Figure 1. BeppoSAX light curves for Ton S 180 in the soft band (top), medium energy band (middle) and hardness ratio light curve (bottom).

Ton S 180, RE J 1034+396 and Ark 564.

2. TON S 180

Ton S 180, an optically bright galaxy with an optical spectrum typical of NLS1, is a strong and variable extreme ultraviolet source detected by the EUVE satellite [11]. Not surprisingly it is also bright in the ROSAT PSPC energy range. Amplitude variations up to a factor 2 on timescales ranging from hours to days have been observed. The 0.1–2.4 keV spectrum is steep with photon slopes ranging between 2.7 and 3.2 [12]. A relatively short (∼20 ksec) BeppoSAX exposure was performed on 1996 December 3. A detailed discussion of this observation can be found elsewhere [13]. The most relevant results can be summarized as follows. Relatively rapid flux variations, by a factor 2 on a timescale of a few $10^4$ s, in both the soft (0.1–3.0 keV) and hard (3–10 keV) X-ray band are clearly present (first two panels of Fig. 1), without any significant evidence of spectral variability (third panel of Fig. 1).

The 0.1–10 keV spectrum requires at least two components: (1) a steep $\Gamma \simeq 2.7$ strong soft component below 2 keV which contains a large fraction of the overall energy output, and (2) a weak hard tail with a 2–10 keV slope $\Gamma \simeq 2.3$ that is significantly steeper than the average value found in “normal” Seyfert 1s and quasars. There is evidence for iron line emission at $\sim 7$ keV (Fig. 2). When fitted with a simple Gaussian, the best fit centroid indicates a high (H–like) ionization state. Ionized iron line emission has been also found in the ASCA observation (Leighly et al. in preparation).

3. RE J 1034+396

RE J 1034+396 belongs to the small sample of AGNs detected by the Wide Field Camera onboard ROSAT at very soft (below 0.18 keV) X-ray energies. The PSPC spectrum is extremely soft and can be modelled in terms of two black bodies with temperatures of $\sim 40$ and $\sim 100$ eV plus an extremely weak hard power law component. Follow-up ASCA observations revealed that the power law was unusually steep: $\Gamma \simeq 2.6$. An ionized iron line at $\sim 6.7$ keV is marginally (at 90% confidence) required [14].
The source was clearly detected by BeppoSAX on 1997 April 18 in both LECS and MECS with a $\sim$ 40 ksec exposure. There is no evidence of flux variability in the BeppoSAX observation, moreover the flux level is in good agreement with the previous ASCA value suggesting a remarkably constant X–ray flux over several years. The 0.1–10 keV spectral energy distribution is dominated by a strong soft component below $\sim$ 2 keV which accounts for more than 90% of the total luminosity, while at higher energies the source is much weaker. The RE J1034+396 continuum emission is best fitted by two blackbodies with temperatures of $55\pm10$ eV and $155\pm20$ eV plus a steep power law $\Gamma = 2.20 \pm 0.24$ (Fig. 3). The overall spectral shape is in good agreement with previous results [14] even if the values of the spectral parameters are slightly different. There is no evidence of iron line emission but it should be noted that the signal to noise at high energies is rather poor.

On the basis of optical and HST ultraviolet observations, it has been argued [15] that RE J1034+396 has one of the hottest big blue bumps of any Seyfert. It is completely shifted out of the UV band and is thus visible at Extreme UV and X–ray wavelengths. This would be consistent with ASCA and BeppoSAX spectral fits. The two blackbodies can be considered as a first order approximation of the high energy tail of a hot optically thick accretion disk.

4. ARK 564

Arakelian 564 is a bright NLS1 observed by ROSAT [1]. The 0.1–2.4 keV PSPC spectrum appears to be complex as a simple steep power law ($\Gamma \simeq 3.4$) provides a very poor fit [17]. The residuals of the power law fit suggest the presence of spectral features typical of warm absorbing gas. Either a line at $\sim 0.8$ keV or an edge at $\sim 1.15$ keV improve significantly the fit quality, however the PSPC spectral resolution prevented detailed analysis.

A $\sim$ 20 ksec BeppoSAX observation has been recently performed (1997 November 14). The first preliminary results of the BeppoSAX observation are summarized below, while a more detailed analysis will be deferred to a future paper.

The light curves in the soft 0.1-3.0 keV LECS energy range and in the 3.0-10 keV MECS energy...
range are shown in the first two panels of Fig. 4. High amplitude variability, with a doubling time of the order of $10^4$ s has been clearly detected at all energies. There is also some evidence of rapid variability at the end of the observation possibly associated with spectral changes as suggested by the hardness ratio light curve (bottom panel of Fig. 4).

The overall 0.1–10 keV spectrum requires at least two components. Either a broken power law or a blackbody plus a power law provide a relatively good description of the continuum emission. In both cases the 0.1–2.0 keV flux is about one order of magnitude greater than the 2–10 keV flux and the 2–10 keV power law is very steep ($\Gamma \approx 2.4$). Iron line emission at $\sim 6$ keV is clearly present (Fig. 5).

The best fit energy: $6.22 \pm 0.30$ keV indicates neutral or mildly ionized iron. The line appears to be broad ($\sigma = 0.65$ keV), however its width is only weakly constrained by the present data.

A single power law gives a poor fit to the low energy LECS spectrum (Fig. 6). The most prominent deviations from such a model are suggestive of the presence of ionized absorbing gas which is common among Seyfert galaxies [16]. When a narrow Gaussian line is added a significant improvement is obtained ($\Delta \chi^2 \approx 40$). The best fit line energy and equivalent width are: $E = 0.86 \pm 0.04$ keV and $55 \pm 24$ eV respectively. An even better description of the low energy data ($\Delta \chi^2 \approx 15$ with respect to the power law plus line) was obtained by adding an absorption edge at $E = 1.38^{+0.17}_{-0.09}$ keV with depth $\tau = 0.30 \pm 0.12$. A detailed discussion on the origin of these spectral features is beyond the scope of this paper, however we note that these results are somewhat surprising as the detected spectral features are rather different from those found in classical Seyfert 1 galaxies [16]. Moreover there are no obvious lines and edges expected at these energies as discussed in [17,18]. Finally it should also be noted that fitting the soft X-ray spectrum with a blackbody model the line and edge are still present although at a lower level of significance.

5. DISCUSSION

The X-ray spectral properties of the 3 NLS1 observed by BeppoSAX are remarkable when compared with those of classical Seyfert 1s and quasars. The spectral shapes are summarized in
Figure 7. The broad band energy distribution of Ton S 180 from optical to X-ray energies [13].

Table 1. The broken power law fits are to be considered as a first approximation of the overall 0.1–10 keV X-ray spectrum. The soft X-ray spectra of RE J1034+396 and Ark 564 can also be fit with the high energy tail of thermal emission models. A two-component model provides an adequate description of the 0.1–10 keV continuum for all the objects in analogy with several broad lined AGNs. However, the slopes of the two components are rather different from those in broad line AGNs [1]. The soft component is much stronger than in “normal” Seyfert 1s, while the 2–10 keV power law slopes are much steeper than the average value ($\Gamma \simeq 1.9$) for Seyfert 1s and quasars in the same energy range [2,3]. The large relative intensity of the soft component and the steep 2–10 keV slopes (see also [8]) have important consequences. Even if the observation of iron lines suggests that reprocessing is occurring at some level, it appears likely that the strong soft component cannot be due only to disk reprocessing, unless there is highly anisotropic emission or a high energy spectrum extending up to extremely high energies.

The strong soft component could lead to a strong Compton cooling of the hot corona electrons and so to a steep hard tail if a significant fraction of the gravitational energy is dissipated in the disk phase [2,3]. This hypothesis is also supported by the similarities between the NLS1 X-ray spectra and those of Galactic black hole candidates (GBHC) in their high state as first suggested in [1,14]. The high states of GBHC are thought to be triggered by increases in the accretion rate resulting in strong thermal emission from a disk accreting near the Eddington limit. If this is the case the disk surface is expected to be strongly ionized which fits nicely with the detection of a ionized line in Ton S 180 [13]. A high \(L/L_{\text{Edd}}\) ratio would also be consistent with the narrowness of the optical lines in NLS1. In fact the optical line width is inversely proportional to \(L/L_{\text{Edd}}\) if the broad line region is virialized and its radius is a function of luminosity alone [1,23,24]. The lack of iron line emission in RE J1034+396 and the low iron ionization state in Ark 564 raise some problems with this interpretation.

Despite the similar X-ray spectral energy distributions (See Table 1) the NLS1 observed so far differ in several other properties. Ton S 180 and Ark 564 show relatively rapid X-ray variability on timescales of the order of $10^4$ s, and spectral variability is probably present in Ark 564. On the other hand the RE J1034+396 light curve appears to be constant over several years.

The imprints of highly ionized absorbing gas are visible in the soft X-ray spectrum of Ark 564,
Table 1
Summary of the BeppoSAX spectral fits

|                  | Single power law (2-10 keV) | Broken power law (0.1-10 keV) |
|------------------|-----------------------------|-----------------------------|
|                  | $\Gamma \times 10^{-12}$    | $\Gamma_s \times 10^{-12}$   | $E_{\text{break}}$ | $\Gamma_h$ |
| TON S 180        | 2.21 ± 0.12                 | 4.2 ± 0.12                  | 2.68 ± 0.07       | 2.5 ± 0.7   | 2.29 ± 0.15 |
| RE J1034         | 2.20 ± 0.23                 | 9.3 ± 0.13                  | 3.24 ± 0.06       | 2.5 ± 0.6   | 2.08 ± 0.35 |
| ARK 564          | 2.38 ± 0.07                 | 1.5 ± 0.11                  | 2.75 ± 0.05       | 2.2 ± 0.5   | 2.37 ± 0.08 |

The absorption column density has been fixed at the Galactic value in all the fits. Fluxes are in erg cm$^{-2}$ s$^{-1}$, break energies in keV. Errors are at 90% confidence for one interesting parameter.

while Ton S 180 and RE J1034+396 are characterized by relatively smooth soft X-ray spectra.

It is also worth noting that RE J1034+396 has strong high ionization iron lines but weak Fe II, while the other two objects have strong Fe II emission and not so strong high ionization iron lines.

Finally the spectral energy distributions (SED) from optical to X-rays are also different. The SED of Ton S 180 and RE J1034+396 are displayed in Figures 7 and 8 respectively.

The data for Ton S 180 suggest that the energy density peaks somewhere in the ultraviolet. The optical–UV light dominates the energy output with a behaviour similar to that of other quasars [13]. The situation is reversed for RE J1034+396 where most of the energy density is found at soft X-ray wavelengths, while the UV continuum is rather weak [13].

Further BeppoSAX observations and coordinated optical campaigns are clearly needed to clarify some of these issues.

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