ROSAT Results on Narrow-Line Seyfert 1 Galaxies

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Abstract

The excellent soft X-ray sensitivity of the PSPC detector onboard the ROSAT satellite provided the first chance to study precisely the spectral and timing properties of Narrow-Line Seyfert 1 galaxies. ROSAT observations of Narrow-Line Seyfert 1 galaxies have revealed (1) the existence of a giant soft X-ray excess, (2) a striking, clear correlation between the strength of the soft X-ray excess emission and the FWHM of the H$\beta$ line, (3) the general absence of significant soft X-ray absorption by neutral hydrogen above the Galactic column, (4) short doubling time scales down to about 1000 seconds, (5) the existence of persistent giant (above a factor of 10), and rapid (less than 1 day) X-ray variability in extragalactic sources. The soft X-ray results on Narrow-Line Seyfert 1 galaxies indicate that their black hole regions are directly visible, further supporting the Seyfert 1 nature of these objects. The extreme X-ray properties of Narrow-Line Seyfert 1 galaxies make them ideal objects for understanding many of the problems raised generally by the Seyfert phenomenon.

Key words: galaxies: active; X-rays: galaxies

1 Introduction

This paper reviews the important ROSAT contributions to the field of Narrow-Line Seyfert 1 (NLS1) research. The excellent soft X-ray sensitivity of the PSPC detector (Pfeffermann et al. 1987) onboard the ROSAT satellite (Trümper 1983), the ROSAT All-Sky Survey data (Voges et al. 1999), and deep ROSAT PSPC and HRI pointed observations provided the best opportunities to study NLS1s before the launches of XMM-Newton and Chandra. ROSAT observations have triggered the rapid growth in the definition of the phenomenological parameters of NLS1s throughout the electromagnetic spectrum, as well as the theoretical modeling of their exciting properties. This is clearly demonstrated
with the papers presented in these proceedings. Fifteen years after the definition of the peculiar optical properties of NLS1s (see the review article of Pogge), followed by a period in which their importance had been suggested (e.g. Halpern & Oke 1987; Stephens 1989; Puchnarewicz et al. 1992), NLS1s now represent an important class of the AGN family, holding many keys to our understanding of the problems posed by the Seyfert phenomenon.

2 The story of IRAS 13224–3809

My NLS1 research started in 1992 with a ROSAT PSPC AO-2 pointed observation of IRAS 13224–3809. The object was proposed for a ROSAT pointed observation because the ROSAT All-Sky Survey observations showed an unusually large X-ray luminosity for a Seyfert 2 classification, as given at the time in the literature. The remarkable X-ray luminosity of a few $10^{44}$ erg s$^{-1}$ was confirmed in the ROSAT pointed observations, and, most surprisingly, we found a light curve with unusually rapid and large-amplitude variability for a radio-quiet AGN. The shortest doubling time was only 800 seconds, and the maximum variability amplitude was about a factor of 4 within a few hours. All this happened in mid-December 1992, and we thought it would be useful to take an optical spectrum of this potentially important Seyfert galaxy. I went to ESO and talked with Bob Fosbury on this matter. One of his colleagues, Adline Caulet, was observing during Christmas time at the ESO 3.6 m telescope using the EFOSC spectrograph, and she actually took the first high-sensitivity spectrum of IRAS 13224–3809 on December 24, 1992. The spectrum showed a narrow H$\beta$ line of less than about 1000 km s$^{-1}$ FWHM and extremely strong Fe II multiplet emission lines around 4500 Å and 5200 Å. Therefore, the new optical observations revealed the NLS1 nature of IRAS 13224–3809, and we found the first clear instance of strong and rapid X-ray variability in a NLS1. During 1993–1994, Henner Fink and I worked out the spectral properties of a few other NLS1 galaxies by comparing the ROSAT spectral slopes and the FWHM of H$\beta$ for NLS1s and broad-line Seyfert 1 galaxies from the Walter & Fink (1993) sample. We saw the first indications of an increasing spread of the soft X-ray spectral slopes with decreasing line widths for Seyfert 1 galaxies. The breakthrough in determining the soft X-ray properties of NLS1s began in the middle of 1994. After I gave a talk at the Institute of Astronomy in Cambridge, U.K., Andy Fabian told me that a student of his, Niel Brandt, was also working on the X-ray properties of NLS1s (e.g. Akn 564) and had found similar results, and he asked me to talk with him. This was the beginning of a most constructive collaboration, and within a couple of months we actually came up with our ‘Figure 8’ showing the relation between the soft X-ray slope and the FWHM of the H$\beta$ line (Boller, Brandt & Fink 1996).
3 NLS1s as an extreme of Seyfert activity

NLS1s were found to exhibit extreme properties when compared with broad-line Seyfert 1 galaxies. Many NLS1s show

- A giant soft X-ray excess up to $\approx 1.5$ keV
- A larger than previously thought power-law slope diversity
- Rapid and large-amplitude variability
- Indications of a highly ionized accretion disk
- Indications of a cooler accretion disk corona

Fig. 1. Schematic illustrations of the broad-band spectral energy distributions of NLS1s (left panel) and broad-line Seyfert 1 galaxies (right panel). The right panel is based on an idea of A.C. Fabian. NLS1s often show extreme soft X-ray excess strengths and unusually steep power-law X-ray continua.

Comparison of the schematic broad-band X-ray energy distributions shown in Fig. 1 illustrates the extreme soft X-ray excess and the generally steeper hard X-ray continua of NLS1s. The hard power-law slope diversity of NLS1s was discovered by Brandt, Mathur & Elvis (1997). Indications of an ionized Fe Kα line are found in the NLS1 Ton S180 (Comastri et al. 1998). In the case of a cooler accretion disk corona, steeper power-law slopes are expected due to the smaller energy increase per scattering of an ultraviolet or soft X-ray photon. A cooler accretion disk corona might be due to stronger cooling by the huge soft X-ray excess photon density. Accepted XMM-Newton observations of carefully selected NLS1s are expected to shed further light on these issues.
4 Optical emission-line correlations with X-ray continuum slopes

4.1 Correlations between the soft and hard X-ray continuum slopes and the FWHM of Hβ

A strong relation between the ROSAT photon index and the FWHM of the Hβ line has been detected in Seyfert 1 galaxies (e.g. Boller, Brandt & Fink 1996; see the left panel of Fig. 2). While Seyfert 1 galaxies with Hβ FWHM greater than 3000 km s\(^{-1}\) have their photon indices confined to a fairly narrow range, with a mean value of about 2.3, NLS1s show an extremely large diversity in their values of the photon index, reaching values of up to about 5. A region with values of the photon index above about 3 and Hβ FWHM > 3000 km s\(^{-1}\) is not occupied by Seyfert 1 galaxies, and it appears that Seyfert galaxies are not allowed to exist in this ‘zone of avoidance.’ In the ROSAT energy band, the photon index serves as a measure of the relative contributions of the soft X-ray excess emission and the underlying power law. Sources with high values of photon index are therefore thought to show the strongest soft excess emission. The Hβ FWHM is a measure of the velocity dispersion in the Broad Line Region. The soft X-ray emission probably arises within a few Schwarzschild radii of the central black hole in the accretion disk, and the emission from the Broad Line Region arises at significantly larger distances (light days to light years; see the paper by Peterson in these proceedings). Therefore, the correlation between these quantities suggests that the emission from the accretion disk determines the velocity dispersion of the line emitting clouds in the Broad Line Region.

A similar correlation has been discovered by Brandt, Mathur & Elvis (1997) between the ASCA 2–10 keV photon index and the FWHM of Hβ. NLS1s again show a larger diversity in the distribution of their photon indices than broad-line Seyfert 1 galaxies. In the 2–10 keV energy band, the spectral energy distribution is dominated by the power-law contribution, which is thought to be primarily formed through Compton scattering processes in the accretion disk corona. A complete understanding of the steeper 2–10 keV X-ray continua in NLS1s has not emerged up to now (see Section 3).

4.2 Seyfert 1 unification through physical processes

A whole set of correlations between the X-ray spectral and timing properties and optical emission-line properties have now been detected among Seyfert 1 galaxies. The optical emission-line properties include the FWHM of Hβ, the strength of the optical Fe II emission (relative to Hβ) and the [O III] λ5007
Fig. 2. **Left Figure (a):** Photon index in the 0.1–2.4 keV energy range as a function of the FWHM of the H$\beta$ line. The photon index serves as a measurement of the steepness of the X-ray continuum. All objects in the diagram are Seyfert 1 galaxies. The NLS1s (H$\beta$ line widths $<\,2000$ km s$^{-1}$) are taken from Boller, Brandt & Fink (1996). The broad-line Seyfert 1 galaxies were investigated by Walter & Fink (1993). A significant correlation between the slope of the X-ray continuum and the FWHM of H$\beta$ is found. Seyfert 1 galaxies with large line widths (FWHM H$\beta$ $>\,2000$ km s$^{-1}$) show a relatively small dispersion in their values of the photon index with a mean of about 2.3. NLS1s show a strong dispersion in their values of the photon index. Some of these objects exhibit values of the photon index up to about 5. A region of the diagram, with values of the photon index larger than 3 and optical line widths larger than about 3000 km s$^{-1}$, is not occupied by Seyfert 1 galaxies. This region is sometimes called the 'zone of avoidance.' **Right figure (b):** Photon index in the 2–10 keV energy range as a function of the FWHM of H$\beta$ (Brandt, Mathur & Elvis 1997). The measurements were obtained with the Japanese X-ray satellite ASCA. In the hard X-ray energy range, NLS1s show a stronger dispersion in their photon indices than previously thought. Typical values of the photon index in the hard X-ray energy band range between about 1.7 and 2.6.

A compilation of X-ray and optical emission-line parameters is given in Table 1. Plausible qualitative interpretations of the strong soft X-ray excess observed in many NLS1s include a higher Eddington accretion rate and/or lower black hole masses. Comptonization may play a role in explaining the steep 2–10 keV power-law slopes found in NLS1s. The postulated higher ionizing photon density from a higher temperature accretion disk might explain the larger size of the Broad Line Regions in NLS1s (see the paper of Peterson et al. in these proceedings). Boroson & Green (1992) argued that a toroidal distribution of the Broad Line Region clouds might prevent ionizing radiation...
from reaching the planar Narrow Line Region (photon screening). This might cause the weak [O III] emission seen in NLS1s. Relativistic Doppler boosting effects or X-ray flares above the accretion disk might explain the rapid and giant amplitude variability detected in some NLS1s (see Section 5).

Table 1
Set of X-ray and optical correlations among Seyfert 1 galaxies (columns 1 and 3). Plausible underlying physical parameters are listed in column 2.

| Broad-line Seyfert 1 | physical parameter | Narrow-line Seyfert 1 |
|----------------------|--------------------|----------------------|
| Weak soft X-ray excess | \( M, M \)          | Strong soft X-ray excess |
| Flat power-law slope  | Comptonization      | Steep power-law slope |
| Broad permitted lines | Ionizing photon density | Narrow permitted lines |
| Weak Fe II           | Cooler corona?      | Strong Fe II |
| Strong [O III]       | Photon screening?   | Weak [O III] |
| Moderate X-ray variability | Relativistic effects? | Extreme X-ray variability |

5 The extreme X-ray variability of NLS1s

In this section I concentrate on the most extreme cases of X-ray variability detected in radio-quiet AGN, i.e. variability with an amplitude above a factor of about 10 in combination with timescales of less than about one day. The X-ray light curves can be characterized by strong flaring events interspersed with periods of relative quiescence. The objects discussed below are the NLS1s IRAS 13224–3809, PHL 1092 and 1ES 1927+654.

5.1 The persistent rapid and giant X-ray variability of IRAS 13224–3809

The first systematic X-ray monitoring campaign for a NLS1 was performed in 1996 on IRAS 13224–3809. All relevant details are discussed in Boller et al. (1997). The most important observational facts can be summarized as: (1) the detection of multiple strong flaring events; (2) the most extreme variability over time is about a factor of 57 in just two days; (3) the light curve appears to be nonlinear or non-Gaussian in character; (4) changes in the accretion rate or the ionization state of a warm absorber are not considered plausible explanations for the extreme variability; (5) the most probable explanations include strong Doppler boosting effects arising from temperature inhomogeneities in the accretion disk (see Sunyaev 1973; Guilbert, Fabian & Rees 1993) or partial obscuration by Compton thick matter (see the paper by Brandt & Gallagher in
In Fig. 3 the ROSAT HRI light curve of IRAS 13224–3809 obtained in 1996 is shown.

![ROSAT HRI light curve of IRAS 13224–3809](image)

Fig. 3. ROSAT HRI light curve of IRAS 13224–3809 obtained during a 30-day monitoring campaign between January 11, 1996 and February 9, 1996. The abscissa gives the Julian date minus 2450093.523 days. The dashed line shows the background count rate as a function of time. At least 5 giant-amplitude variations are clearly visible. IRAS 13224–3809 shows the most extreme X-ray variability measured thus far from active galactic nuclei.

5.2 The large efficiency limit derived from the ROSAT HRI light curve of PHL 1092

In Figure 4 the ROSAT HRI light curve of PHL 1092, a luminous narrow-line quasar, is shown. The largest variability amplitude is about a factor of 14 (see Brandt et al. 1999). The most extreme variability event has $\Delta L/\Delta t > 1.3 \times 10^{42}$ erg s$^{-2}$, resulting in an extremely high efficiency of $\eta > 0.62 \pm 0.13$. The ROSAT HRI observation of PHL 1092 therefore further supports the presence of relativistic motions of the X-ray emitting gas causing giant and rapid flux variations in NLS1s.

5.3 The persistent, rapid and giant X-ray variability of the X-ray bright Einstein NLS1 1ES 1927+654

With a mean 0.1–2.4 keV count rate of 1.26±0.026 counts s$^{-1}$, 1ES 1927+654 is one of brightest AGN detected in the ROSAT All-Sky Survey. Most inter-
estingly, unusually large and persistent variability is detected, making this object, behind IRAS 13224–3809 (Boller et al. 1997), the second radio-quiet AGN showing this type of variability. 1ES 1927+654 was observed during

Fig. 4. *ROSAT* HRI light curve of PHL 1092 obtained during an 18-day observation between July 16, 1997 and August 2, 1997. The abscissa gives the Julian date minus 2450645.120 days. The dashed line gives the background count rate as a function of time.

Fig. 5. *ROSAT* All-Sky Survey light curve of 1ES 1927+654 obtained between 1990 July 11–16 (left panel) and 1990 December 11–21 (right panel). Persistent, rapid and giant X-ray variability is detected throughout the *ROSAT* PSPC observations. The maximum factor of variability is about 17.

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the ‘mini-survey’ for about 5 days between 1990 July 11 and 16 with a total exposure time of 254 seconds. During the normal survey scan operations, 1ES 1927+654 was observed for about 11 days between 1990 December 11 and 21. Unusually strong deviations from the mean count rate are detected in the ROSAT All-Sky Survey observations. Figure 5 shows the ROSAT PSPC light curve of 1ES 1927+654. The left panel refers to the ‘mini-survey’ observations in July 1990 and the right panel gives the count rate variations during the survey scan observations in December 1990. Summing the six data points below a count rate of 0.2 counts s\(^{-1}\) results in a lower count rate level of 0.146 counts s\(^{-1}\). Similarly, summing the three data points above 2.4 counts s\(^{-1}\) results in an upper count rate level of 2.51 counts s\(^{-1}\), the amplitude of variability is about 17. Between days 154.017 and 154.150 the count rate increases from 0.28 ± 0.212 to 1.90 ± 0.43 counts s\(^{-1}\), corresponding to a factor of about 8 within only 3.2 hours.

![1ES 1927+654 - ROSAT PSPC pointing](image)

Fig. 6. ROSAT PSPC light curve of 1ES 1927+654 obtained on 1998 December 8. A strong X-ray flare lasting for about 100 s is detected near the end of the observations. The corresponding isotropic energy is \(\approx 10^{46}\) erg.

1ES 1927+654 was observed with the PSPC detector during the final observation period of the ROSAT satellite on December 8, 1998 (Figure 6). Using a bin size of 10 seconds, a strong X-ray flare becomes apparent between 1110 and 1280 seconds after the beginning of the observations. The count rate variations significantly exceed that of the variations caused by the ROSAT wobble. The isotropic energy emitted in this strong X-ray flare is \(E = 1.7 \cdot 10^{46}\) erg. 1ES 1927+654 is most probably another example showing the presence of relativistic motions of X-ray emitting gas in the nuclei of NLS1s.
6 Summary

Great progress in defining the observational properties of NLS1s has been achieved based on ROSAT and ASCA observations. The observations have shown many NLS1s to have characteristic, unique and extreme X-ray properties. These include the strongest soft X-ray excess emission seen in Seyfert 1 galaxies, steep 2–10 keV power-law continua, and extremely rapid and large-amplitude X-ray variability. The extreme properties of NLS1s have additionally stimulated the theoretical modeling of many aspects of Seyfert activity.

7 Acknowledgements

The idea to organize a workshop on NLS1s began in June 1997 at the ‘German-Japanese Workshop on Sky Surveys’ in Potsdam, during a discussion with Niels Brandt and Martin Ward. In early 1999 we finally decided to organize such a workshop. Günther Hasinger suggested to me that I send an application to the Wilhelm and Else Heraeus Stiftung to support the workshop, which in May 1999 turned out to be successful. Therefore, on behalf of the scientific organizing committee, I would like to thank the WE-Heraeus Stiftung for their financial and organizational support. I am especially grateful to Dr. E. Dreisigacker and Mrs. J. Lang for their constructive and effective help in preparing the workshop. I would like to thank the Physikzentrum Bad Honnef, and especially Dr. DeBrus, for help finding accommodation outside the Physikzentrum and support during the workshop. The scientific success of this joint MPE, AIP, ESO workshop is due mainly to the work of the scientific organizing committee: Jacqueline Bergeron (ESO), Niels Brandt (Penn State, USA), Suzy Collin-Souffrin (France), Reinhard Genzel (MPE), Dirk Grupe (MPE), Günther Hasinger (AIP), Karen Leighly (Columbia, USA), Hagai Netzer (Tel Aviv, Israel), Joachim Trümper (MPE), Marie-Helene Ulrich (ESO) and Martin Ward (Leicester, UK). On behalf of the scientific organizing committee, I would like to thank all the participants for attending the workshop, for their input to the scientific discussions, and for submitting their specific contributions, which we believe will be of great scientific interest for the astronomical community at large.
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