THE BROAD BAND SPECTRUM AND VARIABILITY
OF SEYFERT 1

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ABSTRACT Recent results on the X-ray spectrum and variability of Seyfert 1 galaxies are reviewed. New spectral results from BeppoSAX observations are also presented and briefly discussed.

KEYWORDS: X-rays:galaxies; galaxies:nuclei

1. INTRODUCTION

With Chandra just launched, and XMM and ASTRO-E due to follow suit soon, it is the right time to review what we have learned on Seyfert 1 galaxies from previous generation satellites like ASCA and BeppoSAX, and point out the still open questions, hopefully to be answered or at least addressed by the new generation missions. In particular, I will concentrate here on BeppoSAX results, not only because I worked myself on them but also because it is only now that a general picture from these observations is emerging. Before discussing the BeppoSAX observations, however, let me at least mention briefly the recent results from ASCA and XTE which I consider most significant.

2. RECENT RESULTS ON SEYFERT 1

2.1. Variability

The most exciting result in recent years on variability in Seyfert Galaxies is probably the discovery of periodicity in the flux of the Compton–thin Seyfert 2 galaxy IRAS 18325-5925 (Iwasawa et al. 1998). The discovery has been obtained with an imaging satellite, ASCA; when the field is observed with a better spatial resolution instrument (ROSAT), no evidence for a confusing source is found. The chance of the periodicity being due to a cataclysmic variable (like in the infamous case of NGC 6814, Madejski et al. 1993) or some other confusing source is therefore very low. As periodicity has been observed so far only in one (or two, see below) sources, it is possible that it is a transient event, e.g. a flaring region orbiting around the black hole with a lifetime longer than usual (or being so strong to outshine all other flares simultaneously present). IRAS 18325-5925 has many characteristics typical of the subclass of Narrow Line Seyfert 1 Galaxies (see Boller, 1999, for a review):
large amplitude variation, steep spectrum, possibly ionized disc. One can then argue
that periodicities are better to be searched for in NLS1s rather than in ‘classical’
Seyferts. However, a recent claim of a 33 h periodicity in MCG–6-30-15 by Lee et al.
(2000) could indicate that periodicity may be a not so rare phenomenon, after all,
and that it has been generally missed so far due to lack of long enough observations.

Thanks mostly to RXTE, long monitoring campaigns in X–rays simultaneously
with optical and UV have been performed on a few selected objects, with quite
surprising and important results. In NGC 7469 (Nandra et al. 1998), NGC 5548
(Chiang et al. 1999) and NGC 3516 (Maoz et al. 2000), optical/UV and X–ray
emissions seem to be uncorrelated or, if any correlation exists, is the optical/UV that
leads X–rays, opposite to what expected in the reprocessing scenario. This scenario
(Collin–Souffrin 1991), in which optical and UV emissions arises as reprocessing
in the accretion disc of the hard X–rays, was suggested to explain the too tight
correlation (and lack of delays) between optical and UV fluxes (Courvoisier & Clavel
1991) in some Seyfert 1s (NGC 5548 being one of the best examples). So, the
situation is rather confused and puzzling, as in the same source both the viscous
dissipation and the reprocessing scenario appear to be unviable.

Regarding even longer term variability, the most spectacular result recently has
been the switching off of the “swan’s song” galaxy, NGC 4051 (Guainazzi et al.
1998). When observed by BeppoSAX in May 1998, only the Compton reflection
component and the iron line were visible, while the primary radiation had disapp-
peared. When put in the context (Uttley et al. 1999), this observation demonstrated
that the observed reflected emission occurred in matter distant at least a few light–
months from the nucleus. So far, this is the most convincing evidence for the presence
of large amount of cold circumnuclear matter in Seyfert 1 galaxies.

2.2. Warm absorbers

Warm absorbers are detected in at least half of Seyfert 1s (Reynolds 1997, George
et al. 1998), indicating that the covering factor of the ionized material is fairly large.
The reason why warm absorbers are not observed in all Seyferts is not clear. It may
be due either to a spread in column density and/or ionization structure, or to a
covering factor of the ionized matter less than unity. In the first case, an improved
sensitivity, as for instance that provided by XMM, is necessary to search for small
edges due either to small columns of oxygen or to less abundant elements (e.g.
Neon). In the second case, the ionized material may be observed via emission lines
(e.g. Netzer 1993), and high resolution detectors (gratings, Chandra and XMM, or
calorimeters, ASTRO–E) are needed.

The most interesting recent discovery possibly related to warm absorbers is the
1 keV absorption feature observed in some NLS1s (Vaughan et al., 1999a; Leighly
1999 and references therein). When interpreted as a blend of several resonant lines,
mainly from iron L (Nicastro, Fiore & Matt 1999), this implies that the ionization
structure of narrow and broad lines Seyferts is rather different, not surprisingly
given the different ionizing continuum, especially in soft X–rays. Other possible
explanations include blueshifted absorption edges (Leighly et al. 1997) and oxygen smeared edge from ionized discs (Fabian, private communication; see also Vaughan et al. 1999b). XMM should easily distinguish between competing models.

2.3. The iron line

The iron line in Seyfert 1 galaxies is usually broad (Nandra et al. 1997), likely originating in a relativistic disc (e.g. Fabian et al. 1995). In the two best studied sources, MCG–6-30-15 (Tanaka et al. 1995; Guainazzi et al. 1999) and NGC 3516 (Nandra et al. 1999), the observation of a double–horned and asymmetric line profile, expected in presence of fast orbital motion and strong gravity effects (e.g. Fabian et al. 1989; Matt et al. 1992), makes this interpretation quite strong.

In principle, from the line profile and short term variability in response to variations of the continuum (i.e. the so–called reverberation mapping), it is possible to determine the spin of the black hole and the geometry of the accretion disc and the illuminating source (e.g. Martocchia, Karas & Matt 1999 and references therein). Large sensitivity, coupled with good energy resolution, it is required for these goals. It is possible that even the next missions will not sufficient for this purpose, and we have probably to wait for Constellation–X (e.g. Young & Reynolds 2000) and XEUS. It is worth noting, however, that already with ASCA it has been possible to start studying variations of the iron line in MCG–6-30-15 (Iwasawa et al. 1996; 1999). Even if the results are not yet conclusive, these works demonstrated the potentiality of the method.

While most of the iron lines observed in Seyfert 1s can be explained in terms of relativistic discs, it is not clear whether emission from more distant matter (let us call it the “torus”) is also present. Evidence for this component is scanty, and the only unambiguous cases so far are those of NGC 4151 (e.g. Piro et al. 1999) and of NGC 4051 discussed in Sec.2.1. In the latter case, the discovery was due more to a stroke of luck rather than to systematic searches, and the probability to find other sources switched off seems not very high. More promising, in view of missions like XMM and especially ASTRO–E with large sensitivity coupled with good energy resolution, is to search for narrow iron lines (as the torus should be at a distance such that relativistic effects are negligible).

2.4. The continuum

While there is wide consensus on the fact that the power law index (assuming that a power law is actually a good enough description of the primary continuum: see Petrucci et al., 1999) is typically around 1.8–2 (Nandra & Pounds 1994) and that the Compton reflection is a common ingredient, there are still several open questions: is there a correlation between the photon index and the amount of Compton reflection, as suggested by Zdziarski et al (1999)? How common is the soft excess in Broad Lines Seyfert 1s (there is actually no doubt that it is common in Narrow Lines Seyfert 1s)? What is the typical (if any) cut–off energy in the hard X–ray spectra?
FIGURE 1. The distributions of power law indices, $\Gamma$, of the amount of Compton reflection, $R$ and of the iron line EW. The average values and standard deviations are labeled. In parentheses, the value excluding Mkn 841 are also given.

To address these questions, let me discuss the BeppoSAX observations of a dozen of moderately bright Seyfert 1s.

3. A BEPPOSAX SPECTRAL SURVEY OF SEYFERT 1

In Table 1, the observed sources and the main spectral parameters are listed. When the sources have been observed more than once, the results refer to the combined spectrum if there is not spectral variability, or otherwise to the observation when the source was brightest.

For all sources, the spectral model includes: a power law with exponential cut–off; a gaussian line (or a relativistic line, when it provides a significantly better fit); the Compton reflection continuum. A warm absorber and/or a soft excess have been added if required by the data. The spectral parameters reported in the Table refer to the best fit model, whatever its complexity.

In Fig. 1 the distributions of $\Gamma$, $R$ (the solid angle, in units of $2\pi$, subtended by the reflecting matter, assumed to be observed face–on) and of the equivalent width of the iron line, are given. The results are in agreement with those found by Nandra & Pounds (1994) and Nandra et al. (1997) and based on Ginga and ASCA observations, respectively.
TABLE 1. The best fit parameters for the Seyfert 1s observed by BeppoSAX. For the case of Mkn 841, see the caveats in the text. All errors refer to 90% confidence level for two interesting parameters, i.e. $\Delta \chi^2 = 4.6$.

| Source     | S.E. | $\Gamma$ | R  | EW (eV) | $E_c$ (keV) |
|------------|------|----------|----|---------|-------------|
| NGC 5548$^{1,2}$ | NO   | 1.63$^{+0.04}_{-0.03}$ | 0.44$^{+0.18}_{-0.18}$ | 120$\pm$40 | 160$^{+50}_{-70}$ |
| NGC 3783$^1$   | NO   | 1.71$^{+0.08}_{-0.08}$ | 0.37$^{+0.22}_{-0.22}$ | 190$\pm$65 | 160$^{+90}_{-60}$ |
| NGC 7469$^1$   | NO?  | 2.04$^{+0.05}_{-0.05}$ | 1.1$^{+0.4}_{-0.3}$   | 180$\pm$90 | $>$ 230 |
| NGC 4151$^1$   | ?    | 1.35$^{+0.20}_{-0.20}$ | 0.45$^{+0.20}_{-0.20}$ | 240$\pm$70 | 70$\pm$20 |
| Fairall 9     | ?    | 2.05$^{+0.11}_{-0.09}$ | 1.2$^{+0.7}_{-0.5}$   | 220$^{+60}_{-100}$ | $>$ 220 |
| NGC 5506      | ?    | 2.03$^{+0.09}_{-0.08}$ | 1.5$^{+1.2}_{-0.5}$   | 175$\pm$45 | $>$ 380 |
| NGC 4593$^3$  | NO   | 1.87$^{+0.05}_{-0.05}$ | 1.1$^{+0.4}_{-0.4}$   | 190$^{+90}_{-6}$  | $>$ 150 |
| IC 4329A$^4$  | NO   | 1.86$^{+0.03}_{-0.03}$ | 0.55$^{+0.15}_{-0.13}$ | 110$^{+50}_{-40}$ | 270$^{+170}_{-80}$ |
| Mrk 509$^5$   | Yes  | 1.58$^{+0.08}_{-0.08}$ | 0.6$^{+0.3}_{-0.3}$   | 110$^{+130}_{-60}$ | 70$^{+50}_{-20}$ |
| MCG-8-11-11$^5$| NO   | 1.84$^{+0.05}_{-0.05}$ | 1.0$^{+0.6}_{-0.4}$   | 130$^{+70}_{-50}$ | 170$^{+300}_{-80}$ |
| MCG-6-30-15$^6$| NO   | 2.06$^{+0.03}_{-0.03}$ | 1.2$^{+0.4}_{-0.2}$   | 200$^{+50}_{-60}$ | 160$^{+130}_{-60}$ |
| Mrk 841       | Yes? | 2.16$^{+0.07}_{-0.05}$ | 3.9$^{+1.2}_{-1.2}$   | 290$^{+210}_{-220}$ | $>$ 150 |
| NGC 3516$^7$  | NO   | 2.04$^{+0.03}_{-0.03}$ | 1.4$^{+0.4}_{-0.4}$   | 100$^{+70}_{-60}$ | $>$ 350 |

$^1$ Piro et al. 1999; DeRosa et al. 1999; $^2$ Nicastro et al. 2000; $^3$ Guainazzi et al. 1999a; $^4$ Perola et al. 1999; $^5$ Perola et al. 2000; $^6$ Guainazzi et al. 1999b; $^7$ Costantini et al. 2000.
3.1. The high energy cut–off

Before the launch of BeppoSAX, a high energy cut–off was unambiguously detected only in one source, NGC 4151 (Jourdain et al., 1992). From the analysis of the spectrum obtained summing several sources observed with OSSE, Gondek et al. suggested an average cut–off energy of a few hundreds keV.

From Table 1, it can be seen that a high energy cut–off is positively detected in about half of the sample. The detected values range from 70 keV (NGC 4151) to 270 keV (IC4329A). When only a lower limit can be obtained, the values are generally consistent with the measured ones. The plot of the e-folding energies vs. the power law index is shown in Fig. 2. While there is no obvious correlation between the two parameters, there is a tendency for flat sources to avoid high values of the cut–off energy. Whether this reflects something intrinsic to the spectra, or simply the fact that it is easier to determine high energy cut–offs in flat sources, cannot be said with the present data.

3.2. The soft excess

Only two out of 13 sources (namely Mkn 509 and Mkn 841) in the BeppoSAX sample discussed here present evidence for a soft excess. Even if for three sources (NGC 5506 and NGC 4151, which have a large intrinsic absorption, and Fairall 9, for which the LECS instrument was switched off, for technical problems, for almost all

FIGURE 2. The high energy exponential cut–off, $E_c$, versus the photon index $\Gamma$. 
the observation) we cannot say anything, the soft excess appears to be the exception rather than the rule.

For Mkn 509, the inclusion of a soft excess (in the form of a steeper power law dominating below about 1 keV) improves significantly the goodness of the fit and provides a more astrophysically sound global solution (Perola et al. 2000). For Mkn 841, a warm absorber fits the spectrum almost as well as a black body soft excess, but from ASCA it seems that the warm absorber is not very relevant in this object (see e.g. Reynolds 1997). In both sources, the shape and luminosity of the soft component remains rather undetermined, and what can be said is that a steepening of the spectrum occurs below 1 keV or so. Whether there is a curvature in the primary X–ray emission, or there are two different components, it is impossible to establish.

3.3. The iron line and Compton Reflection

In Fig. 3 the iron line EW is plotted against $R$. In the reprocessing scenario, the two quantities are expected to be strongly correlated (George & Fabian 1991; Matt, Perola & Piro 1991). The error bars, however, are too large to really check this hypothesis. The relatively small probability (3.4%) that they are not correlated is mainly due one point, i.e. Mkn 841 (but see next paragraph).

More interesting and instructive is the comparison between the average values of the two quantities (Fig. 1), as it can be used to estimate the iron abundance, which turns out to be consistent (say, within a factor of 2 or so) with the cosmic value.

3.4. Are $\Gamma$ and $R$ correlated?

In Fig. 4 $R$ is shown against the photon index. A correlation between the two quantities is evident, the probability that they are not correlated being only 1.3% if Mkn 841 is excluded, and less than 0.1% when it is included. However, a word of caution is necessary here. The two parameters are strongly correlated in the fit procedure (see also the discussion in Nandra et al. 2000). If, for some reason, the photon index is miscalculated, and e.g. a value steeper than real is found, a larger $R$ is immediately obtained. Let me use the case of Mkn 841 as an example. If the soft excess is modeled with a black body, the results for $\Gamma$, $R$ and the iron EW listed in Table 1 and presented in the figures are obtained. An even steeper spectrum ($\Gamma=2.27$) and, correspondingly, larger $R$ (4.6) is obtained with the warm absorber model. Conversely, if the soft excess is modeled by a power law, the photon index is significantly flatter ($\Gamma=1.75$) and $R$ reduces to 1.5 (but the line EW remains fairly large, e.e. 350 eV).

Therefore, I believe that the issue of the reality of the $\Gamma$–$R$ correlation is still open, and can be further addressed only by much more sensitive missions like XMM (but the energy band may be not broad enough) or Constellation–X.
FIGURE 3. The iron line EW vs. $R$.

FIGURE 4. $R$ vs. $\Gamma$. 
4. CONCLUSIONS

The main results from the BeppoSAX observations of a sample of Seyfert 1 Galaxies can be summarized as follows:

- In most sources there is no evidence for a soft excess. In only two sources, Mkn 509 and Mkn 841, a steepening of the spectrum below about 1 keV seems required by the data. Whether it is due to a curvature of the primary emission, or to an altogether distinct component, is impossible to say.

- A high energy cut–off with $e$–folding energy typically in the range $\sim 100–200$ keV is observed, when the quality of the data is good enough.

- The power law index, $\Gamma$, and the amount of reflection component are clearly correlated, confirming the findings of Zdziarski et al. (1999). However, it is possible that such a correlation is not real, but partly or entirely due to the fact that the two parameters are strongly correlated in the fit procedure. Let us suppose that some values of $\Gamma$ are miscalculated, either because there are other components not taken into account, or because a power law is a too simple model (e.g. Petrucci et al. 1999). In this case, a correlation between $\Gamma$ and $R$ would be immediately found, as the quality of present (and of course past) data is not sufficient to measure the amount of Compton reflection independently of the shape of the primary continuum.

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