Constraints on the High Energy Continuum of Seyfert galaxies from RXTE Color-Color and Color-Flux Diagrams

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Abstract. We report on some results from a three-year program of RXTE observations of 4 Seyfert galaxies: NGC 4051, NGC 5548, MCG-6-30-15 and NGC 5506. We focus here on color-color and color-flux diagrams obtained using the count-rates of the PCA instrument in different energy ranges: 3–5, 5–7 and 7–10 keV.

The data of the different sources show interesting trends in the different color-color and color-flux planes. These trends are quite similar from one source to the other, even in the case of the narrow line Seyfert 1 NGC 4051 which exhibits strong flux and spectral variability.

We discuss these results in term of a simple spectral model: a power law with high energy cut-off + reflection + Iron line, with the scope of understanding the relations between the observed variations of different components and the physical causes of the variability.

The main aim of the project was to study the X–ray flux variability of NGC 4051, NGC 5548, MCG-6-30-15 and NGC 5506 the sources on long time scales (Uttley et al., in preparation). For that reason, we tried to sample the largest possible range of the variability time scales from sub–daily to yearly, so the objects were observed with a different rate at different parts of the whole 3 years period. Typically, each observation had an average exposure time of \(\sim 1\) ksec. Here we focus on the spectral variability observed in these 4 objects.

1. The Data

The data was reduced using FTOOLS v.4.2. The light curves include only the PCA, top Xenon layer data, where the PCA is most sensitive. PCA “good times” have been selected from standard 2 data using the “normal” criteria for faint sources: “elv > 10, time since SAA > 20 minutes, electron0,1,2 < 0.1, offset < 0.02 and PCUs 0,1 and 2 on” (the other PCUs were on and off occasionally and that is the reason they were not included in the analysis). All the light curves include Epoch3 data ONLY, and the background estimation
Table 1. The RXTE observation log

was done using the latest L7 model for faint sources. We have reported in Table 1 the observation period as well as the number of pointings for each object. In Fig. 1, we have plotted the 7-10 keV light curves of the 4 Seyfert galaxies. The Narrow-Line Seyfert galaxies NGC 4051 exhibits larger amplitude than the other, as typical of this class of objects.

Figure 1. 7–10 keV light curves of the four objects of our sample during the 3 year period of RXTE observations. Note the different scales.

2. The Method

2.1. The Hardness Ratios

We use the count rates in four bands of the PCA instruments of RXTE: 3–5, 5–7 and 7–10 keV. We have then computed two different hardness ratios HR1
and HR2 defined as follows:

\[ \text{HR1} = \frac{(7 - 10 \text{ keV})}{(3 - 5 \text{ keV})}, \quad \text{HR2} = \frac{(7 - 10 \text{ keV})}{(5 - 7 \text{ keV})} \]  

HR1 is thus sensitive to the variability of the continuum and HR2 to the variability of the equivalent width (EW) of the neutral Iron line expected near 6.4 keV.

2.2. The Model

We have computed the color-color and color-flux relations expected with a cut-off power law + reflection + neutral Iron line model. We have used the PEXRAV model (Magdziarz & Zdziarski, 1995) of XSPEC v10.0.

We have computed the hardness ratios with different values of the spectral index (\( \alpha \)) between 0.3 and 1.6, reflection normalization (R=0, 1, 2) and Iron line EW (0, 250 and 500 eV). The column density for NGC 5506 being large (\( N_h \approx 10^{22} \text{ cm}^{-2} \)), it was also included in the computation for this object.

3. Results and Discussion

3.1. The Color-Flux Diagrams: variability of the continuum shape

The color-flux plots HR1 versus the (3–5 keV) count rates of the four galaxies are shown in Fig. 2. They have quite similar trends even in the case of the Narrow-Line Seyfert 1 NGC 4051: the spectrum softens when the flux increases. The objects show spectral variation \( \Delta \alpha \approx 0.3 \) for flux variations of factor of two. At very low flux however, NGC 4051 exhibits a different behavior. We obtain significant correlations using the Spearman rank-order test. The corresponding Spearman coefficients \( r_s \) are reported, for each object, in Table 2, with the best fit linear parameter (the solid black lines in Fig. 2). Roughly similar slopes are found for each object.

For comparison, we have over-plotted in Fig. 2 the hardness ratios computed with the PEXRAV model, assuming a variation of the spectral index with constant broad band (1-1000 keV) flux. Different curves correspond to different values of the reflection normalization R (0, 1 or 2).

We see that the color-flux trends are relatively well explained by variation of the photon index at a constant broad band flux.

| Object Name | \( r_s \) | \( P \) | \( a \) | \( b \) | \( \chi^2_P \) |
|-------------|----------|--------|--------|--------|----------|
| NGC 5506    | -0.52    | \~10^{-10} | -0.050\pm0.005 | 0.57\pm0.006 | 278/127  |
| NGC 5548    | -0.51    | \~10^{-10} | -0.068\pm0.007 | 0.547\pm0.008 | 259/134  |
| MCG-6-30-15 | -0.49    | \~10^{-9}  | -0.064\pm0.007 | 0.484\pm0.008 | 244/124  |
| NGC 4051    | -0.70    | \~10^{-19} | -0.057\pm0.005 | 0.460\pm0.008 | 310/118  |

Table 2. Linear best fits (i.e. \( y=ax+b \)) of the color-flux diagram HR1 vs. (3–5) keV plotted in Fig. 2. Errors in both coordinates are taken into account. We also list in the first two columns the Spearman rank-order correlation coefficient \( r_s \) and its significance \( P \).
Figure 2. HR1 vs (3-5) keV color-flux plots for each objects of our sample. The black solid lines are the best linear fits (parameters reported in Table 2). We have also over-plotted the color-flux trends predicted by PEXRAV for different reflection normalization (from top to bottom R=0(blue line), R=1 (red line), R=2 (green line)), assuming a constant broad band (1-1000 keV) flux. The photon index is reported on the blue curves.

4. The Color-Color Diagrams: Variability of the Iron Line

| Color-color | Object Name | a       | b       | $\chi^2$ |
|-------------|-------------|---------|---------|----------|
| HR2-HR1     | NGC 5506    | 0.78±0.09 | 0.25±0.05 | 92/127   |
|             | NGC 5548    | 0.90±0.11 | 0.25±0.05 | 93/134   |
|             | MCG-6-30-15 | 0.99±0.12 | 0.20±0.05 | 98/124   |
|             | NGC 4051    | 0.54±0.08 | 0.37±0.03 | 132/140  |

Table 3. Linear best fits (i.e. $y=ax+b$) of the different color-color diagrams plotted in Fig. 3. Errors in both coordinates are taken into account.

We have plotted, in Fig. 3, the color–color diagrams HR2-HR1 for each object of our sample. We have also reported the hardness ratios predicted by PEXRAV for different photon index and line EW. It appears that:
The two hardness ratios are roughly proportional (best linear fit parameters reported in Table 3) meaning that the line flux follows the continuum variability.

The line EW keeps quite constant during spectral changes. For harder spectra, the EW slightly decreases.

5. Conclusion

All four objects of our sample exhibit flux and spectral variabilities, the larger ones being observed in the Narrow Line Seyfert galaxies NGC 4051, as typical of this class of objects.

The color-flux diagrams show systematic trends, quite similar for each object, even in the case of NGC 4051 (at large flux): the spectra always soften when the flux increases.
• The color-flux trends are relatively well explained by variation of the spectral index (between ~0.6 and ~1.1) at constant broad band flux.

• The EW of the Iron line keeps roughly constant during spectral variability meaning that the Iron line flux follows the continuum. This result supports the idea that the Iron line is produced by reflection from the matter which is very close to the X–ray emitting region.

References

Papadakis I., Petrucci P.O., Maraschi L., et al., 2001, in preparation