BROADBAND EMISSION PROCESSES OF ACTIVE GALACTIC NUCLEI

Master’s Thesis in Physics
Presented by
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22.09.2017

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Abstract

In my Master’s Thesis I present two topics related to Active Galactic Nuclei (AGN). These objects are very luminous and emit across the whole electromagnetic spectrum. Radio-loud AGN feature jets, very long and collimated streams of matter, which are observable in all wavelengths as well. The visibility in the radio band is due to synchrotron radiation emitted by electrons. This emission process is the first main topic of this thesis and addressed in detail, covering the complete derivation from the Maxwell equations to the final, self-absorbed spectrum produced by electrons, which follow an energy dependent power-law distribution. As synchrotron radiation is discussed in many publications, but the equations do not always look the same at first sight, an elaborated comparison is conducted.

Numerical methods are necessary for the calculation of a spectrum if the electron distribution does not allow an analytical approximation for the radiation. For power-law distributed electrons one can either determine a numerical or an analytical solution, which is why I use a numeric integrator for the calculation of the spectra first and then compare the results with the analytic approximation of the integrals. Additionally I show problems, which arise from using numeric methods.

The second main topic of this work presents a systematic cross-correlation study of two X-ray satellites, XMM-Newton and NuSTAR. A good cross-calibration between different instruments is essential for multiwavelength observations, which help understanding astrophysical sources due to analyses in the complete spectral range. For the study, simultaneous observations of AGN are analysed using two different methods. The comparison of the photon indices, which describe the slope of the power-law, allows to detect differences in the calibration of both instruments. By simultaneously fitting both spectra in the overlapping energy band, one can determine the difference in the flux normalisation.
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4 Systematic study of simultaneous observations of AGN by XMM-Newton and NuSTAR

4.1 Introduction

Performing simultaneous observations with different satellites allows us to study energetic sources like X-ray binaries or active galactic nuclei (AGN) in a broader emission regime. As radiation is rarely confined to only a small emission range, we can get better insights in the behaviour of those sources by combining data from all over the spectrum. When studying accreting objects in the X-rays, emission features in the region of the iron Kα line (6.4 keV) are important for the analysis of relativistic line broadening near black hole systems. However, good results can only be found when the underlying continuum is well known which requires knowledge about the spectrum in the hard X-rays. Additionally, relativistic reflection effects which range from the lowest energies (1 keV) up to the Compton hump (30 keV) cannot be observed with only one instrument so far. Simultaneous observations in different energy ranges therefore improve the study of energetic sources, variable sources in particular. In order to gain good and reliable results from a simultaneous observation it is necessary to have a very good cross-calibration between the involved satellites. Since a perfect calibration is not possible to achieve, calibration uncertainties introduce discrepancies in the data analysis and impact the determination of astrophysical values. The aim of the work presented in this chapter was to help improving the cross-calibration between XMM-Newton and NuSTAR by analyzing as many simultaneously performed observations of AGN as there were publicly available at the end of June 2016. This work was a project performed at the European Space Astronomy Center (ESAC) under the supervision of Norbert Schartel and Maria Santos-Lleo.

4.2 The satellites XMM-Newton and NuSTAR

The X-ray satellite XMM-Newton (Jansen et al., 2001) was launched by the European Space Agency (ESA) in 1999. It observes soft X-rays in an energy range from 0.2 to 12 keV with two Reflection Grating Spectrometers (RGSs) and three European Photon Imaging Cameras
Systematic study of simultaneous observations of AGN by XMM-Newton and NuSTAR

Figure 4.1: The satellites XMM-Newton and NuSTAR

4.3 Data

4.3.1 Extraction

The data was extracted with the standard pipelines. The observations by XMM-Newton were extracted using XMM-Newton Science Analysis System (SAS) version 15.0.0 aiming to achieve a maximum S/N. Data from the NuSTAR spacecraft was extracted using the NuSTAR Data Analysis Software (NUSTARDAS) package (v.1.4.1), using nupipeline and the calibration database CALDB20150316 for creating cleaned and calibrated data products. In order to create strictly simultaneous observational data, we used the FTOOLS mgtime to merge the gti-files from the observations of both spacecrafts into a common one which was then applied to all observations presented here. All spectra have been binned for a higher S/N ratio. While for the EPIC-pn spectra we used a constant S/N ratio factor of 10 for binning, for the FPM spectra we constantly binned 10 channels together. The complete data set used in this work is given in Table 4.1.
4.3 Data

4.3.2 Data Analysis

All spectra were analysed with xspec 12.8.2 using the wilms abundances (Wilms et al., 2000) and the vern cross sections (Verner et al., 1996). Two different approaches were used to gather information about the differences in the XMM-Newton and the NuSTAR calibration.

Method 1 includes fitting an EPIC-pn spectrum with a physical model, then applying the model without further change of the parameters to the NuSTAR data in order to compare how well the model for the XMM-Newton data fits to the NuSTAR spectrum.

Method 2 involves simultaneously fitting spectra from EPIC-pn and FPMA/FPMB, respectively, from 3 to 10 keV and retrieving a cross-normalisation constant as well as differences in the power-law indices of the best fit. All errors are 90% confidence unless stated otherwise.

4.3.2.1 Method 1: Comparison of ratios

In Method 1 the ratio of data points to a model are used. The first step is finding a physical, well fitting model for the XMM-Newton spectrum. This model is then applied to the NuSTAR spectrum without fitting the model again. The comparison of the NuSTAR data with the model is done by the ratios, which are directly obtained from xspec.

Whether the observation of a source was used for this method can be seen in the column Method of Table 4.1. The applied physical models for each source are given in Table 4.2. Each model contains a power-law (pegpwrlw or bknpower for a broken power-law). For galactic absorption we used tbnew_feo\textsuperscript{1} a simple version of the new version of tbabs (Wilms et al., 2000). For a source showing relativistic reflection, we applied the relxill model (García et al., 2014). relxill includes a primary spectrum, which originates in a corona surrounding the accretion disc and is also a power-law, as well as it takes into account the reflection onto the accretion disc. In that way, we can see relativistically broadened emission lines, particularly the iron K α line. In case of the presence of a warm absorber or an extensive soft excess in the spectra, we included the model warmabs or a simple blackbody (bbody), respectively.

\textsuperscript{1}http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/
# Systematic study of simultaneous observations of AGN by XMM-Newton and NuSTAR

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<td>60001110007</td>
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Table 4.1: All observations included in the data sample. The spectra were studied using two different methods; the column Method shows whether a source was included in both analysis methods or just one.

As an example, simultaneous spectra from EPIC-pn, FPMA and FPMB are shown in Fig. 4.3 (Ark 120) and Fig. 4.4 (Swift J2127.4+5654). For all models the NuSTAR spectra show discrepancies, since the models were fitted to data from the XMM-Newton satellite. This approach allows comparing the difference between both spacecrafts indirectly by looking at the ratios. Note that the comparison between EPIC-pn and the FPM detectors does not allow to make a statement about the correlation between the MOS and the FPM detectors. In the ratio plots a slope is visible (e.g. see Fig. 4.3 and Fig. 4.4), causing the FPMA/FPMB values to be higher than the values of EPIC-pn up to 7 keV.
Figure 4.3: Fitted EPIC-pn spectrum (black) of Ark 120 with spectra from both detectors of NuSTAR (FPMA: red, FPMB: green) in the upper window. In the lower window ratio values for model vs. data are given for each spectrum.

Figure 4.4: Fitted EPIC-pn spectrum (black) of Swift J2127.4+5654 with spectra from both detectors of NuSTAR (FPMA: red, FPMB: green) in the upper window. In the lower window ratio values for model vs. data are given for each spectrum.
In order to get rid of systematics caused by the different models and sources, and to see whether this slope is present in all spectra, we merged all of the ratio plots together in one plot. Figure 4.5a shows the calculated mean values with the according standard deviation, while Fig. 4.5b shows the median with the median absolute deviation. In both plots the ratios unveil deviations between the FPM spectra and the model in the energy range from 3 to 7 keV.
4.3 Data

Figure 4.6: Simultaneously fitted EPIC (black) and FPMA (red) spectra of 3C 273. In the lower window the ratio values for model vs. data are given for both fits.

4.3.2.2 Method 2: Simultaneous fitting

Simultaneous fitting in the common energy band can be used to compare different instruments directly. An approach can be adding a cross-normalisation constant to the model, which depicts the difference in flux normalisation. The other way is to compare the photon indices, $\Gamma$ (the value of the power-law slope), for fitting the same model simultaneously to both spectra and allow only this parameter to vary.

All observations used for this method can be found in the column Method of Table 4.1. All fits were done from 3 to 10 keV simultaneously for two detectors each (EPIC-pn & FPMA, EPIC-pn & FPMB) per source. We also fitted the spectra from both FPM detectors simultaneously to check whether there are significant discrepancies between them.

The models used for the sources are shown in Table 4.3. They do not differ much from the models from method 1, but some are kept simpler, because executing the fit in a smaller energy range did not require a blackbody anymore to describe the soft excess which is present below 2 keV. Two example spectra for simultaneous fits are shown in Fig. 4.6 (3C 273) and Fig. 4.7 (MCG−6−30−15).

The first task is to compare the flux normalisations by using a cross-normalisation constant. A source specific model was fitted to the EPIC-pn spectrum while keeping the same parameters for the FPM spectra (similar to Method 1). In addition to the models shown in Table 4.3 a constant, $c$, was added and set to 1 for the EPIC-pn spectra, but kept free for the FPM spectra. This cross-normalisation constant represents the difference in the flux normalisations of both instruments. The mean value for this constant is given in Table 4.4. The error was derived through error propagation of the uncertainties determined in the fit. The mean value is fairly close to 1, but a look at the distributions for both FPM detectors (see Fig. 4.8a and Fig. 4.8b) reveals some scattering around the mean value. A difference between the FPM detectors is
Figure 4.7: Simultaneously fitted EPIC (black) and FPMA (red) spectra of MCG−6−30−15. In the lower window the ratio values for model vs. data are given for both fits.

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<th>Source</th>
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<th>Reference</th>
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<td>Lohfink et al. (2013)</td>
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<td>$tb_{\text{new}}_{\text{feo}}\times\text{pegpwrlw}$</td>
<td>Stuhlinger et al. (2004)</td>
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<td>Centaurus A</td>
<td>$tb_{\text{new}}_{\text{feo}}(\text{pegpwrlw}+\text{zgauss})$</td>
<td>Fürst et al. (2016)</td>
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<td>Fairall 9</td>
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<td>Parker et al. (2016)</td>
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<td>Wilms et al. (2001)</td>
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<td>Mrk 915</td>
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Table 4.3: Models applied on EPIC-pn and FPM spectra in Method 2

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<tr>
<td>EPIC-pn/FPMA</td>
<td>1.004 ± 0.034</td>
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<tr>
<td>EPIC-pn/FPMB</td>
<td>1.041 ± 0.034</td>
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<tr>
<td>FPMA/FPMB</td>
<td>1.034 ± 0.019</td>
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Table 4.4: Cross-normalisation constants, $c$, for FPMA and FPMB.

Apart from three observations all derived constants lie within the 90% error region for both FPM detectors. The three exceptions are observation 11, 13 and 14 which belong to Centaurus A, Mrk 915 and HE1136-2304 respectively. While obs. 14 is inside the error region accounting its errors, obs. 11 and 13 are definitely off. In the case of Centaurus A, being a close and bright
Figure 4.8: Cross-normalisation constant distributions of FPMA and FPMB for all observations. The dashed line marks the mean value and the 90% error region is coloured.

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<th>Source</th>
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<td>EPIC-pn/FPMA</td>
<td>$1.020 \pm 0.017$</td>
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<tr>
<td>EPIC-pn/FPMB</td>
<td>$1.062 \pm 0.018$</td>
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</table>

Table 4.5: Cross-normalisation constants, $c$, for reduced sample.

source, this offset can be explained with pile up effects being present even though we tried avoiding those in the extraction by excluding the innermost region of the source. For Mrk 915 we have no explanation for the low cross-normalisation in this source. Additionally, observation 6, 9 and 10 have large errors exceeding the $1\sigma$ region which makes those results less trustworthy. Excluding these observations (6, 9, 10, 11, 13 and 14), we get larger cross-normalisation constants (see Table 4.5). Another task was comparing the photon indices for different sources in order to test the
calibration of both instruments. For an ideal cross-calibration between both satellites, those values should be the same. In Fig. 4.9 a direct comparison of the photon indices $\Gamma$ for XMM-Newton and NuSTAR is shown. We observe a general offset which shows that the FPMA/FPMB spectra have steeper power law slopes than spectra from EPIC-pn. This seems to be present in all observations. In a more direct comparison, Fig. 4.10 presents $\Delta \Gamma$ from 14 observations of 8 sources over flux, showing there is no correlation with flux and therefore no pile-up effects present. The mean differences for EPIC-pn-FPMA, EPIC-pn-FPMB and FPMA-FPMB are shown in Table 4.6. The observation from Centaurus A was excluded from this sample, because it shows a much higher discrepancy between the slopes in XMM-Newton and NuSTAR data which might be due to pile up. Note that $\Delta \Gamma$ is much smaller for the comparison between both FPM detectors than between the two satellites.

Another way to look at the results is via a distribution in a histogram. The difference $\Delta \Gamma$ is shown for all 16 observations in Fig. 4.11a and Fig. 4.12a. For both histograms we used a bin size of $\Delta \Gamma = 0.01$ in order to get a clearer overview of the distribution. Since the value at $\Delta \Gamma = 0.4$ (from spectra of Centaurus A) is clearly aside the other results and was already excluded in the calculation of the mean $\Delta \Gamma$ (see Table 4.6), we ignored it. Figure 4.11b shows the remaining columns. In order to look at the normal distribution fitted to that data, we excluded also the two observations which had $\Delta \Gamma > 0.2$ (Mrk 915 and NGC 4593). The remaining data was fitted by a normal distribution of $f(x) = A \cdot \exp(-(x - x_0)/\sigma)^2)$. The same was done for the FPMB detector (see Fig. 4.12). Values with $\Delta \Gamma > 0.2$ were excluded again, which concerned again the observation of Centaurus A.

The parameters $x_0$ and $\sigma$ of the Gaussian fit are shown in Table 4.7 for both histograms. Note that here, $\sigma$ is only a 68% confidence error. While the fit delivers good results for the comparison of EPIC-pn and FPMA, it is more problematic in case of the EPIC-pn-FPMB comparison. There the uncertainties on both parameters are too large to give reasonable constraints, because the values are more spread than in the comparison with FPMA. Over all we find very similar results for the histogram approach as in Table 4.6. The difference of the photon index $\Gamma$ between the EPIC-pn and FPM spectra indicates a principal, energy dependent mis-calibration in either, or in both of the two instruments.

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Table 4.6: Mean values for $\Delta \Gamma$.

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<th>$\sigma$</th>
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<td>EPIC-pn/FPMB</td>
<td>0.136 ± 0.060</td>
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</table>

Table 4.7: Parameters for a Gaussian fit to the distribution of $\Delta \Gamma$ in a histogram. Note that here, the error $\sigma$ is just 68% confidence.
Figure 4.9: Direct comparison of photon indices $\Gamma$ for XMM-Newton and NuSTAR. The ideal case would be that the data points are on the line of equivalence which is not observed.

Figure 4.10: Individual $\Delta \Gamma$ over flux of source.
4 Systematic study of simultaneous observations of AGN by XMM-Newton and NuSTAR

4.4 Comparison with other studies

So far only one cross-calibration analysis between XMM-Newton and NuSTAR was published (Madsen et al., 2017a). They performed a full analysis of the cross-normalisation constants between the satellites Chandra, NuSTAR, Swift, Suzaku, and XMM-Newton for 3C 273 and
4.5 Outlook

Further studies are necessary for the progress of improving the cross-calibration between XMM-Newton and NuSTAR, since we could see that there can be quite different results even for the same source. The difference of $\Delta \Gamma \propto 0.1$ in the power-law slopes is found to be consistent over all the sources and observations, regardless of the model. An explanation can be a principal, energy dependent mis-calibration in either one or both of the instruments.

The cross-normalisation constant $c$ reveals differences in the flux normalisations of both satellites and shows some variations for which the origin has yet to be determined.

Recently there was an observation of the Crab nebula by NuSTAR without its mirrors (Madsen et al., 2017b). They find the true intrinsic flux to be 12% higher than the flux measured in an observation that includes the NuSTAR optics. Observing the stray light from the Crab allowed

PKS 2155-304. Since 3C 273 was in the sample that we analysed, we can compare their and our results directly. They used a simple power-law and $\text{tbabs}$ for absorption, very similar to our model for 3C 273 (see Table 4.3). However, they used a fitting range from 3 to 7 keV, while we used all data between 3 and 10 keV. Another difference lies in the data extraction for which we used SAS version 15.0.0 and Madsen et al. SAS version 14.0.0. The values of $c$ and $\Delta \Gamma$ are given in Table 4.8. Although they did not include a power-law index comparison in the paper, they showed the values for $\Gamma$, being derived in individual fits, which we used for calculating the correspondent $\Delta \Gamma$. While the difference in the power-law slope matches for the FPMA detector, there is nearly no difference between the FPMB detector and EPIC-pn according to Madsen et al. (2017a). Additionally the cross-normalisation constants between the EPIC-pn and the FPM detectors found by Madsen et al. (2017a) are much larger than the values found in this work.

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Madsen et al. (2017b) to measure new detector absorption parameters, which resulted in an update of the detector absorption files in CALDB20160606. The surveys of AGN and other astrophysical sources depend on the cooperation of different satellites, because radiation processes, e.g., synchrotron radiation, exist in broad spectral ranges, which can only be studied by many different instruments working together.
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Acknowledgements

First and foremost I want to thank my supervisor Prof. Dr. Joern Wilms for his support, encouragement and advice. I am very grateful for the opportunity to attend the AGN conference 2016 at Garching, the IBWS conference 2017 at Karlsbad and Prof. Wilms’ support for my traineeship at ESAC, whose project became part of this thesis. I deeply want to thank Norbert Schartel and Maria Santos-Lleo for the wonderful and interesting time I had while working at ESAC. In addition, I want to thank all the trainees, who made the five months in Madrid so much fun, especially Alessandra, Kjell, Harry, Aleksi and Vedad. Then, of course, I am very grateful to be part of the Remeis community, without which the Remeis observatory would not be such a welcoming and pleasant working place. Sincere thanks are given to all the Remeisen. I want to thank Matthias Kühnel and Ralf Ballhausen for their help with the NuSTAR data extraction and give a big thank you to Thomas Dauser, Sebastian Falkner and Javier Garcia for their help during the preparation of my first conference talk. At this point I also want thank my office mates for hilarious conversations and apologise for my over-use of the word "Bieberkacke". I am looking forward to many years more of Remeis skiing and overturning during the annual canoeing, as well as (spontaneous) barbecues and pool parties. Somehow, public outreach became important to me during the last year, probably also because of Simon Kreuzer. I am very grateful that he suggested to give a lecture about multiwavelength astronomy together at a "Schülerakademie", because it was a great experience and a lot of fun. A big thank you to Basti, Tommy and Tobi for improving my thesis through helpful comments and fancy plot ideas. Last but not least I want to thank my family and friends for their support.

This thesis has made use of ISIS functions (ISISscripts) provided by ECAP/Remeis observatory and MIT (http://www.sternwarte.uni-erlangen.de/isis/). In this thesis I use observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA, NASA, as well as data from the NuSTAR mission, a project led by the California Institute of Technology, managed by the Jet Propulsion Laboratory, and funded by NASA. This work has made use of the NuSTAR Data Analysis Software (NuSTARDAS) jointly developed by the ASI Science Data Center and the California Institute of Technology.