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dr hab. Piotr Lubiński, prof. UZ
Instytut Fizyki, Wydział Fizyki i Astronomii
Uniwersytet Zielonogórski
ul. Prof. Szafrana 4a, 65-516 Zielona Góra

Referee's Report on the Doctoral Dissertation
Fluorescent Iron Lines in Various Types of Radio-Loud Active Galactic Nuclei
submitted to the Jagiellonian University by mgr Karthik Balasubramaniam

1 Introduction

The PhD dissertation of mgr Karthik Balasubramaniam focuses on an interesting phenomenon of an iron fluorescence in the vicinity of supermassive black hole residing in the centre of radio-loud active galactic nuclei. This type of study is of major importance because the accretion onto compact objects is one of the central topics of modern astronomy. Since the accretion disk is, besides the molecular torus, the main source of the iron emission, an analysis of the iron line(s) is a valuable tool to diagnose the properties of the disk and the central plasma region. In the radio-loud systems of a particular interest are the disk-jet and plasma-jet interactions, involving the jet emission mechanism and jet structure evolution.

Studies of the disk and plasma emission are difficult for obscured systems, predominantly the AGN observed at a large inclination angle, where the torus, outer parts of the disk and outflowing material absorb most of the central radiation. For bright radio-loud AGN like blazars the non-thermal jet emission dominates the X-ray spectra, thus also the radio-loud systems seen nearly face-on are not good choice for disk studies. Therefore, taking into account that the radio-loud AGN are less numerous than the radio-quiet AGN and also, on average, more distant, their disk properties are less known and demand a closer look.

Diagnosis of the iron line component allows to constrain various properties of the disk and plasma, like geometry, ionization state or temperature. This tool can be applied for various types of radio-loud systems, characterized by different luminosity, orientation, stage of the jet duty cycle or other parameters, for a closer examination of the jet launching and evolution mechanisms. There are other, more distant sources of the iron fluorescence, such as the torus or galactic/intergalactic media affected by the jet. Thus, the iron line investigation can be used to study the interaction of these regions with the central components of the AGN system, also for the obscured objects.

In a broader context, a study of the inner accretion disk properties through the iron line examination is the main tool to get insights on the extreme gravity region for the systems with a strong jet. An importance of such a research has grown recently, after successful application of the global radio telescopes network to visualize the very central region of several radio-loud galaxies. On the other hand, in a much larger scales, an iron line based diagnosis of the jet transformation in the radio-loud AGN enhances the possibilities of investigating various aspects of the jet influence on the galaxy and intergalactic medium evolution. Adding such information can provide a significant input for the modern, advanced simulations of the galaxy evolution.

2 Dissertation contents

The dissertation is of a medium length and consists of 131 (18+113) pages. The contents is divided into 5 main chapters accompanied by a supplementary material. These main chapters are Introduction, the three chapters presenting the results, and Conclusions and final remarks. Presentation of the research results in the chapters 2–4 has a form of the three papers published by the Author and his collaborators:

- *Signatures of the Disk-Jet Coupling in the Broad-line Radio Quasar 4C+74.26*,
  G. Bhatta, Ł. Stawarz, A. Markowitz, K. Balasubramaniam et al., ApJ 866, 132, 2018 (9 citations);
- *Chandra View of the LINER-type Nucleus in the Radio-loud Galaxy CGCG 292-057: Ionized Iron Line and Jet-ISM Interactions*,
  K. Balasubramaniam et al., ApJ 905, 148, 2020 (1 citation);
- *X-ray Emission of the γ-ray Loud Young Radio Galaxy NGC 3894*,
  K. Balasubramaniam et al., ApJ, accepted, 2021.

The main chapters are preceded by the Abstract, table of contents, list of figures, list of tables and Acknowledgments. The list of references appears at the end of the dissertation.

In the Introduction the Author presents basic facts about radio-loud AGN, observations of AGN in the X-ray band and a review of various satellites observing the sky in that band. Radio-loud AGN are characterized within a general information about accreting supermassive black holes, with the basic AGN components described. Presentation of the X-ray emission from these systems is concentrated on the reflection components. Then, the satellites review deals with both contemporary and future observatories.

Chapter 2 is the original paper on the timing and spectral studies of the broad-line radio quasar 4C+74.26. Here the main contribution of the Author is a detailed analysis of the X-ray spectra with a complex model, revealing a relativistically broadened iron fluorescence line. The paper on the spectral studies of the LINER radio galaxy CGCG 292-057 forms Chapter 3. A detection of the ionized iron line is discussed within the jet-ISM interactions and LINERs properties context. Then, the Chapter 4 is the recent paper presenting the results of a study of the young radio galaxy NGC 3894. Here the analysis is concentrated on the reflected (line) and absorbed components of the X-ray spectra. The last chapter contains a summary of the dissertation results and conclusions, with an emphasized importance of the iron fluorescence line studies for various types of radio-loud AGN.

There are 43 figures and 8 tables presented in the dissertation. The list of references consists of 301 positions, predominantly cited in the three papers included.

3 Remarks

3.1 Major issues

Section 2.3.3
One of the main results of the spectral analysis done for 4C+74.26 is the inner disk truncation radius. This result strongly depends on the reflection component fitted to the spectrum, which, in turn, strongly depends on the fitted continuum. The Authors assumed for the latter an exponentially cut-off power-law model, with the high-energy cut-off fixed at 180 keV, similar to the value of 183 keV fitted by Lohfink et al. 2017 to the average NUSTAR spectrum.

As shown in Fig. 2.5, spectral data quality above 50 keV is poor and the cut-off energy cannot be well constrained, thus fixing it appears a good solution. However, was it investigated how the obtained result depend on the assumed value of that parameter? In addition, it is well known fact that the exponential cut-off is a poor approximation of the true high-energy cut-off of the Comptonized spectra (e.g., Zdziarski et al., 2003, MNRAS, 342, 355; Lubiński et al., 2016, MNRAS, 458, 2454), especially for the low-temperature (kT_e < 100 keV) plasma. Thus, besides a check of different values of the exponential cut-off energy it might be desired to check the spectral fit result with the relxill model option assuming a continuum in a form of the Comptonized spectrum (nthcomp model).

Section 3.2.2

The presence of the 6.7 keV line is one of the major results of this research. In the plots of Fig. 3.5 showing the binned spectra fitted with various models there is only one channel with an excess at the position of this line, whereas there are several other discrete spectral features at lower energies, with the excess present in more channels. Therefore it appears desired to assess the statistical reliability of the ionized iron line detection with some simulations.

First of all it will be good to show the original un-binned spectrum to present the 6.7 keV region. Then, since the Authors used C-statistic during fitting, it might be reasonable to use the approach proposed by J.S. Kaastra (2017, A&A 605, 51) to do the statistical tests comparing the fitted models with and without the line. On the other hand, the Author can do a test with the spectra simulated with his model F, but without the line component, checking the probability that a line with similar intensity can be observed by chance.

Section 3.2.2, Table 3.2 and last paragraph

In the Table 3.2 there are two parameters quoted with only the upper uncertainty, is this a misprint? Then, the concluding comments on the spectral modelling seem to not fully correspond to the results presented in Table 3.2. The comment (iii) about model D appears too strong: both the gas temperature and powerlaw index look acceptable and this model gives much better fit than models A-C, and is, in fact, the best model taking into account the C-stat/DOF ratio. Could the Author comment this issue, why model D was not considered further, e.g., with the iron line component added?

Sec. 4.2.2

Similarly to the issue raised above for Sec. 3.2.2, here again there are some doubts about the way the statitistical significance of the line and other spectral components was determined. The spectral data around 6.4 keV shown in Fig. 4.4. are more convincing here than in the case of Fig. 3.5, however, the line is still quite weak. Moreover, the feature around 4.6 keV should be also modelled to correctly assess the model quality.

First of all, F-test should not be used for the line component or non-nested models pairs, see e.g. Protassov et al., 2002, ApJ 571, 545. Thus, the significance of both the 6.4 keV line and the plasma components cannot be tested with this test. The Author might use the sample-size corrected Akaike criterion (N. Sugiura, 1978, Commun. Stat. - Theory Methods, 7, 13) for the model selection. The other approach can be based on simulations, as proposed above for the Sec. 3.2.2 issue. In the case of un-binned data the significance results of the 6.4 keV line can be also compared to the 4.6 keV line significance.

3.2 Minor issues

Sec 1, first paragraph

Mass range for SMBH should rather start from 10^5 solar masses. For example the mass estimate for NGC 4395 is about 280 000 solar masses, with a relatively small uncertainty.

Sec.1.1, first paragraph, last but one sentence

The explanation of the quasars nature proposed by Hoyle and Fowler is one of the early attempts, incorrect, as it was established later, in 1970 and 1980-ties. Thus this citation here seems strange, despite that the proposed mass of the object is of a right order.

Sec. 1.1.3, second paragraph

References for the numbers characterizing the BLR should be provided.

Section 1.2.1, first paragraph

The "Compton hump" component appears also in the case of a weak or moderate reflection, not only when the SMBH is Compton-thick. Of course, the use of the word "hump" might depend on a relative amplitude of that component.

Sections 1.2.1, 1.2.2

Besides the X-ray reflection also a forward scattering in surrounding media, e.g. in the torus, should be mentioned here. Reflection is only one of several possible ways of reprocessing the radiation on the way to the observer.

Section 1.2.2, first paragraph footnote
An earlier, more general reference should be given here, e.g. some textbook on atomic physics.

Section 1.3.1, first paragraph
Collecting area of XMM-Newton depends on energy but does not exceed 4650 cm^2, not 120 m^2 quoted by the Author.

Section 3.2.1, Fig. 3.3
The number of photons is quite small but maybe it can be checked if the high-energy band with the iron line, e.g. above 3 keV, shows a similar surface brightness profile?

Section 4.2.2, Figure 4.6 and Table 4.2
In the Table 4.2 there are about 750 degrees of freedom quoted for each fitted model. However, the plots in Fig. 4.6 show much smaller number of channels. Were the spectra rebinned for the plotting purposes in this case?

Section 4.3.1, last paragraph on page 85
The Author mention about a need to observe the source with XMM-Newton or NUSTAR. In fact, the NuSTAR observation was done on August 2nd, 2020, and data became public recently. Thus, it might be interesting if the Author tries to quickly analyze those data, just to look if the results are consistent with the Chandra spectral analysis.

Section 4.5.2, last paragraph and Table 4.5
The last but one sentence stating that the Γ value is close to 0 and the N_H value is unconstrained for the 'small binning' does not agree with the results presented in Table 4.5. Why?

3.3 Editorial corrections

The dissertation is written in English, the text is clear and concise. There is a some number of misprints, listed below.

Abstract
'relativisticly' –> 'relativistically'
'broad-lined' –> 'broad-line'

Sec 1.1, first paragraph
'diskovery' –> 'discovery'

Sec. 1.1.1, first sentence
'diskussed' –> 'discussed'

Page 14, last sentence
'even horizon' –> 'event horizon'

Section 1.3.4, second paragraph
'co-alined' –> 'co-aligned'

Section 1.3.4, third paragraph
'Cesium' –> 'Caesium'

Many figures, e.g. Figs. 1.2, 2.2, 2.3, 2.4, 3.2, 3.3, 3.4, 3.5, 3.6, 4.1, 4.2, 4.3, and also Tables 2.1, 3.1, 3.2, 4.1 should appear after the first mentioning in the text.

Fig. 2.6
Missing abscissa axis label in the middle panel.

Fig. 3.5
Contrary to the caption, the middle left panel does not seem to correspond to model C with the line included.

Figure 3.6
The upper right and lower left panels' caption is exchanged.

Sec. 3.4, last paragraph
'luministy' –> 'luminosity'

Section 4.1, first sentence
'lenicular' –> 'lenticular'

Section 4.2, second paragraph
'parameteres' –> 'parameters'

Section 4.2.1, last sentence
'analzyed' –> 'analyzed'

References list
Fukuzawa et al., Patrick et al., and Richards et al. appear two times with the same data.

4 Conclusions

The PhD dissertation submitted by mgr Karthik Balasubramaniam contains valuable and original results for the three radio-loud AGN. In the case of the 4C +74.26 the Author's contribution to the project, providing the value of the inner radius of the accretion disk, reinforced the interpretation of the observed lag between the radio and optical emission in terms of variability driven predominantly by the magnetic field perturbations. For the second AGN, CGCG 292-057, the Author's analysis showed that the iron fluorescence from the central part of this merger system comes mostly from the ionized gas of the broad-line region, illuminated by the nuclear emission. The Author's results obtained for the third object, a young radio galaxy NGC 3894, demonstrate that it can be another AGN, where the origin of the iron line emission remains uncertain when interpreted within the X-ray Baldwin effect scenario, as it happens recently for some classes of the sources.

From the scientific point of view, the thesis prepared by mgr Balasubramaniam substantially contributes to the field of high-energy astrophysics related to the accretion/ejection processes in the supermassive black hole systems. The Author demonstrated an ability to reduce and analyze properly spectra from the NuSTAR and Chandra satellites. For the NuSTAR spectrum a relatively complex model was fitted. The Chandra spectral analysis was supplemented by an analysis of the surface brightness profiles to better define the spectral extraction regions. Interpreting the results the Author performed various calculations, aiming at examination of the luminosity, ionization and other parameters of the studied objects. The results were compared with the literature data for relevant types of AGN and discussed in a relation to various aspects.

Presentation of the results in the thesis is clear, with a convincing interpretation. Despite several concerns related to details of the statistical analysis the Author proved a high level of his expertise to carry on the research tasks. In conclusion, the thesis fully satisfies all formal criteria and I recommend that it is admitted to the public defence.

Piotr Lubiński

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