Bartycka 18, 00-716 Warsaw, Poland
tel: +(4822) 841 00 41, +(4822) 3296 100
fax: +(4822) 841 00 46
email: camk@camk.edu.pl
http://www.camk.edu.pl

Polish Academy of Sciences
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The Faculty of Physics, Astronomy
and Applied Computer Science,
Jagiellonian University,
Kraków, Poland

"A Comprehensive and Novel Analysis of the Chandra X-ray

Observatory Data for the Pictor A Radio Galaxy"

doctoral thesis by Mgr. Rameshan Thimmappa,

supervised by dr hab. Łukasz Stawarz

Referee's report

The PhD thesis by Rameshan Thimmappa presents the state of art for multi-epoch X-ray data analysis of extended source – famous active galaxy Pictor A. The source is the Broad Line Radio Galaxy with asymmetric large scale radio morphology, so called FRII. The above PhD thesis is composed of three publications, where Mr Thimmappa is the first author. Two of those paper are already published, while the first is the conference proceedings and the second is regular paper published in Astrophysical Journal (ApJ) – one of the best journals in the field. The third paper is submitted to ApJ. Such structure of the dissertation composed of the exact text of the publications is widely accepted, but it has to be preceded by a valuable introduction and summary section.

The thesis consists of five chapters, the first of which is a broad introduction, three middle are results, and the last chapter contains summary and conclusions. The introduction is very extended and it touches different topics from instruments operating in different energy bands, through *Chandra* X-ray observatory, active galactic nuclei, radiative processes, to the summary of Pictor A emission. On one side, such introduction is quit long (accounts for 41% of the thesis), but it is very clearly and well written, so I had really good time reading this. I have only one technical remark, that some abbreviations are not given in the text (CXC – abbreviation given in p. 18, but used in p. 16, no abbreviation for HETG, and LETG). Nowadays, it is common to prepare abbreviation dictionary on the beginning or on the end of the thesis, to avoid text searches, especially in the field of X-ray astronomy and satellites, where each of several instruments on one satellite has its own name. Three minor points need to be clarify, to be sure that we are thinking the same (author and me). 1) Seyfert 2 galaxies very often show Compton thick shape-like X-ray spectrum, which means that absorption is not “true absorption” (by different ions or atoms) but it is caused by non-elastic Compton scattering. 2) The division on thermal and non-thermal radiative processes does not show the fact that Comptonization can also be thermal process, which is for instance in case of accretion disk and neutron star atmospheres. 3) The author says that “Soft X-ray excess is of the unknown origin”, but there are at least two possibilities, which in my opinion should be mentioned – to be precise: the first possibility is the Comptonization on the warm corona, the second - relativistically blurred reflection.

The second chapter presents interesting technique to reduce X-ray diffused emission from extended sources applied for the central spot of Pictor A radio galaxy. It requires simulations of pile-up effect and PSF. And this is very interesting task, and I miss here the broader introduction. The algorithms used by author are quit unique and it will be nice to write more about them. But the author only introduces the way of computations, but he does not fully explain the physical justification. For instance: why the Gaussian profile is added to PSF “Tast # 2” analysis? Is it typical treatment or invented by author? The whole thesis is about X-ray observations, I miss broader introduction to data reduction of spatially resolved spectra and extended emission with the use of exposure maps. How response matrices and exposure maps were created? I personally know that PSF simulation proceeds with the use of ChaRT and MARX software, but PhD thesis should be a good portion of new expert knowledge for wider community, so it is important to clarify what “taking into account all the relevant detector issues” (page 49) means? And why authors are fitting beta-profile component to PSF? Mr. Thimmappa analysed the same data as Hardcastle et al. 2016, and the difference is the treatment of PSF function and the different model used for pile-up. The author is suggesting that extended wings used for PSF by Hardcastle et al 2016 may be explained by the contribution of hot gaseous atmosphere of the host Pictor A nucleus. But we cannot easily verify such statement. Furthermore, the conclusion that: “the ring-like morphology of this excess supports our conclusion that it is an artefact of the instrumental pile-up effect” requires better justification in the form of presenting the same simulations with or without pile-up and checking the surface brightness profile fit improvement. Concerning an iron line, I will appreciate the analysis of significance of adding the Gaussian component. Typically, the statistic should be reported i.e. how much we low down \Chi^2 after adding Gaussian component (remembering the decrease of degrees of freedom). Furthermore, the contour plots should be given to clarify the confidence levels. In addition, the mc_sig tool (Houck & Denicola 2000) is available for X-ray spectra, in the aim to search if the line component is real or made by the photon noise. But of course, the paper is printed as conference proceedings and it may show that we should be careful with data analysis.

The third chapter is the published paper on the Western hotspot of Pictor A located at the projected distance of 4 arcmin from nucleus. It contains the introduction to the general view about jets. And again, it repeats some informations from chapter 1 (broad introduction), but very fast comes to more interesting details without deeper explanation of techniques used for data analysis. For instance: why the Galactic absorption is frozen during spectral fitting? Why spectra are not fitted up to 10 keV? The data covers 15 years of observations. Mr. Thimmappa makes detailed image deconvolution of the hotspot for each pointing, investigating its flux variability. PSF modelling and pile-up effects are taken into account. As a result, we receive an exposure-corrected images at 0.5px resolution averaged over PSF realizations and superimposed with radio contours. The most interesting is a measurement of counts variability in North and South hotspot. North region dominates, but in both there is a monotonic decrease of the net count rate by about 30% over 15 years. It can be produced by CCDs' degradation, but it is possible that photon leakage from N to S region occurs. The author aimed to resolve X-ray structure into i) jet-like feature, and ii) the disk-like structure perpendicular to the jet axis. Finally, the shock structure is transversely unresolved even at the sup-px *Chandra* resolution ~ 0.25 arcsec < 200 pc (the best resolution ever obtained in X-ray astronomy). All analysis is impressive showing the power of X-ray observations made in photon counting mode, where CCD works as spectrometer, and each pixel gives spatially resolved count-rate.

The same analysis tools for X-ray data are used in Chapter 4, where Eastern lobe of Pictor A is studied. The X-ray data are superimposed with VLA observations in polarized radio-signal, but it is not clear to me who made the radio maps? Are they made by author of these thesis, or downloaded from archive? And again, the author is showing the distribution of important quantity which is the Faraday rotation measure (RM), but there is no introduction what this quantity means, and what are the units? Typically the unit of RM is rad/m2 and the value depends on the magnetic field and the line of sight electron density. I know that Mr. Thimmappa and his collaborators know it, but PhD is broadly addressed to many other readers, and good introduction should clarify major points considered in the thesis. And again Mr Thimmappa shown his very good ability to work with spatially resolved spectra of low counts, demonstrating double structure of the E hotspot superimposed with RM map. For spectral analysis the author used three models, when the one APEC, which is the emission of collisionally ionized plasma, gives directly the emitting gas temperature of 8.22 keV. I personally thing that the APEC model should be fitted when emission lines are visible in the spectra, but for sure it should be fitted with a free Galactic hydrogen column density parameter, which may change the value of temperature. But even if the temperature is determined with Galactic absorption frozen, why the value of obtained temperature is not plausible? I appreciated the figure of confidence contours, but I miss the value of best fit model. All point/compact X-ray sources analysed in this chapter do not possess obvious optical counterpart. The most interesting filament A is elongated and extends at least three tens of kpc in projected distance and it is inclined with respect to the jet axis. The temperature agrees with larger amount of thermal gas found in other radio galaxies, only if PL + APEC model is fitted. This is very interesting conclusion, but still the requirement for APEC model is the only gas temperature. The conclusion about the relation of RM and magnetic field strongly depends on the gas density. I miss the discussion on the gas density.

Overall, the thesis by Rameshan Thimmappa presents important input in our knowledge of jets and shock regions observed in different energy bands. It demonstrates how complicated, complex and not always unambiguous is the work with X-ray data. Mr. Thimmappa revealed that severe instrumental pile-up, the PSF modelling with updated pile-up model, and on the end the different image deconvolution may change the final results in spectral and image analysis. He presented his knowledge of the most actual software and tools of the *Chandra* mission, which are constantly upgraded and developed by *Chandra* Data Center. His conclusions concern both the methods of the analysis and the nature of the source. In particular Mr. Thimmappa found that the hot gaseous atmosphere of the host may contribute to the radiative output of Pictor A up to ~30 px, and it should be taken into account when analysing PSF extended wings. He clearly demonstrated that the so called "grade migration" in the pile up detector may strongly contribute to the emission when the iron line Fe K_alpha is visible. The gradual flux decrease, which may also be instrumental, was noticed over 15-years of monitoring of the Western hotspot. In case of radio loud AGN, the correlation between X-ray and radio emission is a subject of particular interest. Mr. Thimmappa indicated newly detected bright X-ray filament extended at least three tens of kpc, which displays anti-correlation between X-ray brightness and polarized radio intensity, accompanied by the decrease of RM. And responding to his thought expressed in the last sentence of the thesis, I write in this report: yes, Your effort does provide a notable contribution to the modern high-energy astrophysics – the field I work as well.

Summarizing, the PhD thesis of Mr Thimmappa contains novel analysis of all available *Chandra* data of Pcitor A radio source. The source has point-like unresolved nucleus, and in all cases detailed PSF should be modelled to extract surface brightness of the nucleus, Western Hotspot and Eastern lobe. The data analysis contain all techniques: spectral, timing and spatial analysis. Each paper ends with interesting conclusions showing high complexity of X-ray data analysis, comparison to radio contours, and the amount of non-solved problems. The presented thesis fully proved that the author is aware of those problems, he made a big effort to extend his knowledge about X-ray data reduction and analysis, and for sure he can work in this field on the highest possible level. Summarizing, the presented thesis fulfil all the formal and customary requirements, and I recommend to proceed to further steps needed to award Mr Rameshan Thimmappa the PhD title.

With Best Regards

Prof. dr hab. Agata Różańska