Referee report on the doctoral thesis of Dominik Gronkiewicz

Warm Coronae for Magnetically Supported Disks in Accreting Black Holes

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The thesis of Dominik Gronkiewicz focuses on theoretical aspects of modelling the excess of emission in soft X-ray spectra observed in accreting stellar-mass black holes in X-ray binaries (XRB) in our galaxy, as well in unabsorbed active galactic nuclei (AGN). The aim of the thesis is to provide a physically well motivated models of the origin of this component.

The prominent component of observed X-ray spectra of both classes of accreting black holes is non-thermal power-law emission in the range of energies of a few keV up to tens or hundrets of keV with a photon index of 1.8 – 2. The soft X-ray excess (SXE) refers to an excess of observed emission in the range of 0.1 – 1 keV with respect to a power extrapolated from the hard X-ray spectra (the 2 – 10 keV) down to the energies of soft X-rays (0.1 – 2 keV). This relatively broad and powerful component has been observed in numerous Seyfert I galaxies and radio-quiet quasars and often carries a significant fraction of the source total X-ray luminosity. The emission peaks below 1keV and separate fitting of the power-law in the range of SXE often gives a photon index around 2.5, a considerably higher value then the photon index of the power-law component at higher energies. While there is a general consensus that the hard X-rays originate in very hot and optically thin corona in the vicinity of accreting black hole, the origin of the SXE still remains an open question. Nowadays, there are two competing scenarios of how this spectral component is formed.

In blurred ionized reflection models the SXE is attributed to the reflection of X-ray radiation from optically thin corona on the upper layers of the accretion disk where the matter is partially ionized. SXE results in part from a radiation scattered by free electrons, but predominantly from a forest of fluorescent emission lines from atoms in the disk, which are typically at low X-ray energies. These spectral lines are then blurred by relativistic effects due to high orbital speed of the matter in strong gravitational field near the black hole, producing featureless emission spectrum just in the energy range corresponding to SXE.

In the competing scenario, two sources of non-thermal emission are assumed. In addition to the very hot and optically thin corona that produces power-law emission at high energies, there is also a less energetic ($T \sim 1$keV) region of moderate optical thickness ($\tau \sim 10 - 20$) surrounding a colder accretion disk. Usually a slab geometry is considered. The seed photons from the underlying cold accretion disk undergo multiple scatterings in the warm media before reaching the surface with approximately Wien spectrum and energies in the range of corresponding to SXE. Simplified models that take into account the energy balance between the disk and warm corona suggest that the observed spectra are compatible with a rather extreme scenario, where almost entire accretion power is dissipated in the warm corona and the underlying disk remains passive. This is in clear contradiction with classical accretion disk models, where local accretion power is proportional to the pressure and one therefore expects highest dissipation near the equatorial plane. This suggests that simple models of disk vertical structure should be modified to include also the coronal region and energy transport between the two components.

In the thesis the author presents his long-term effort to derive vertical structure of both disk and corona from the 'first principles'. Although by first principles are here meant mostly parameterized models of generation and dissipation of magnetic energy and its vertical transport through the disk inspired by results of numerical simulations, in my view it is an important step forward, linking a detailed physics of accretion flows with properties of the observed radiation. In this sense, the author offers a complete story of vertical energy transport in the flow: a part of the mechanical energy of the flow is channeled into the magnetic energy of the ordered toroidal magnetic field in the dynamo processes occurring mostly near the equatorial plane. The generated toroidal field buoyantly raises transporting the magnetic energy to upper layers of the flow. During the buoyant rise some part of the magnetic energy is dissipated (either as Ohmic heat or through the reconnections in the current sheets between to regions of antiparallel toroidal field), heating the plasma above the equatorial plane. The matter cools down emitting a black body radiation at its local temperature and increasing the vertical radiative flux. The radiation further heats up the upper layers of the disk, where it is also Comptonized before emerging to the observer. The author founds his model on results of non-radiative local magneto-hydrodynamic (MHD) simulations (mostly Savelsen at al., 2016) and the parameterization of the MHD processes introduced by Begelman et al. (2015) in his model of magnetically elevated accretion flows. To this he adds a simplified radiative transfer for the frequency-integrated quantities under the gray-atmosphere approximation and solves the energy balance between magnetic and radiative field. The radiation processes taken into account are bremsstrahlung and electron scattering. As a result, he obtain a detailed model of the vertical structure of the flow including both the cold disk and warm corona components together with predictions about the temperature and the optical thickness of the corona. The predicted optical depths are in good agreement with the values inferred from observations ($\tau \sim 5$ in the case of XRB and $\tau \sim 20$ in case of AGN) as well as averaged temperatures of the coronae ($T \sim 10^6 - 10^7$K in both cases). The solutions for the vertical structure also allows him to evaluate the fraction f of the total liberated energy that is released in the corona ($f \equiv F_{\rm out}/Q_{\rm cor}$ with $F_{\rm out}$ and $Q_{\rm cor}$ being a total radiative flux leaving the system and total heating rate per unit surface in the corona) to obtain $f \lesssim 0.7$, which is not as much as indicated by the simplest models of energy balance, but in my view already this result indicates that the effort of the author represents an important step in the right direction.

In addition, at some heights above the equatorial plane, the local balance between the magnetic heating and net radiative cooling may lead to thermally unstable equilibria, where for a small isobaric change of temperature the heating rate raises faster then the cooling rate. Since the magnetic heating rate is practically independent of the temperature, the condition of the instability is negative isobaric temperature gradient of the cooling. The flow then typically tents to find stable equilibria at a different temperature, which is possible because the cooling is not a single-valued function of the temperature. The author explores in details regions of instability for his solution and discuss the role of the instability in connection to properties of concrete observed sources.

I found subject of the thesis very actual and the methodology used by the author fully adequate. The idea to use parameterized but well motivated models of generation and evolution of toroidal magnetic field in the turbulent environment of accretion flows together with inclusion of main relevant radiative processes to build a self-consistent model of the disk-corona vertical structure goes well behind the attempts of self-consistent modelling made so far. In principle, predictions of the model may be directly compared with observations of real sources to constrain basic physical parameters of both MHD and radiative processes involved.

The thesis of Dominik Gronkiewicz consists of four chapters. While the first chapter serves as a general introduction to the subject, the remaining three chapters contain reprints of author's three papers (Paper I, II and III) published during his PhD study that have already passed the referee process. In the following I summarise main finding of the author in each chapter and list questions and small remarks that came to my mind while reading the thesis.

Introduction

Chapter 1 is a general introduction to the subject. It is very well written and also exceptionally helpful for readers outside the subject since most of the ideas followed by author in his work are clearly described here in a very compact way. The author first introduces accretion from the observational point of view, summarising a rich phenomenology behind X-ray observations of AGNs, XRBs and ultraluminous X-ray sources (ULXs). The properties of corona as a main source of hard X-ray radiation are briefly outlined, as well as the famous 'Q'-pattern showing the spectral evolution of galactic XRB in the hardness-intensity diagram. The author then moves to the main subject of the thesis, SXE, observations of which are presented in much greater details, including a brief descriptions of available theoretical models used for fitting observed spectra (NTHCOMP). The need for self consistent modelling of the whole X-ray spectra that links different emission processes occurring in different parts of the source (disk, hot and optically thin corona, warm and optically thick corona) as done for the first time on the phenomenological level by Haardt and Maraschi (1991) and more recently by Hagen and Done (2023), is emphasised. The author then focuses on physical models of accretion flows with particular attention paid to magnetically supported accretion flows. Both analytic models and numerical simulations of accretion disk dynamo activity are briefly discussed. Two pages are devoted to the thermal instability and its occurrence in accretion flows. In the rest of the chapter the author presents main goals of the thesis, gives a summary of main achievements and possible directions for the future work.

Although I enjoy brevity of this chapter and admire ability of the author to fit such huge amount of information into a rather short but still smooth text that is pleasant to read, some subjects are described so briefly that they may lead to some confusions of the reader. One example is a description of angular momentum transport in the disk on page 33 that correctly describes the mechanism behind the magneto-rotational instability but completely omits the fact that this instability drives the MHD turbulence and it is the latter one what is mostly responsible for the enhanced transport of angular momentum in accretion disks.

Paper I

Paper I introduces the model of magnetically heated corona. The author derives set of four first-order ordinary differential equations describing local generation and transport of the radiation flux, magnetic structure and vertical hydrostatic equilibrium. These four equations are equiped by one nonlinear algebraic equation giving local thermal balance between magnetic heating and radiative cooling. Author also clearly identifies contributions of two main cooling processes: the bremsstrahlung and electron scattering. The equations are supplied by four boundary conditions either in the euqatorial plane, or at the surface of the flow that is taken at the height, where the gas pressure decreases to 10^{-5} of the equatorial magnetic pressure. Most notably, at this surface the author requires the sum of the radiation and magnetic fluxes to coincide with the total power released at the same radius by the standard Shakura-Sunyaev disk. Since a large fraction of the energy is escapes in the form of Poyinting flux, this opens a question whether this release cannot be accompanied also by significant mass flux and whether the model does not also predict strong outflows from the disk.

Solutions of the model equations are found numerically using relaxation method. This is a standard approach as the shooting method converges poorly and requires extreme accuracy of the integration scheme for strongly nonlinear problems. The relaxation method is also suitable for situations when one needs to systematically explore large parameter space – one may conveniently use result of a previous calculation as an initial guess for the new solution with slightly changed parameters.

In Paper I, the author concentrates on solutions whose parameters correspond to accretion flows in XRBs and explores large range of radii (from ISCO to $25R_\mathrm{S}$, R_S being Schwarzschild radius), various accretion rates ($\dot{m} \equiv \dot{M}/\dot{M}_\mathrm{Edd} = 0.002 - 1$, $\dot{M}_\mathrm{Edd}$ being the Eddington accretion rate) and magnetization of the disk (the magnetic parameter α_B between 0.01 and 0.3). This way he obtains a large sample of possible solutions. The qualitative behavior is similar in all cases. The temperature vertical structure shows a clear separation between disk and corona regions. Inside the disk, the gas and radiative temperatures almost equal and decrease only by a factor of few before reaching their minima at the boundary between the disk and the corona region. Inside corona both temperatures become decoupled. While the radiation temperature continues in decay, the gas temperature steeply raises towards the surface of the flow. Similar division is also apparent in other quantities. While the main cooling mechanism in the disk region is bremsstrahlung, the corona is mostly cooled by electron scattering. Similarly, the main contribution to the total pressure is gas pressure in the vicinity of the equatorial plane, while it is dominated by magnetic pressure inside the corona.

The solutions obtained are further analyzed for the presence of thermal instability in the coronal region. It is found that the solutions enter the region of thermal instability only for small accretion rate ($\dot{m} \sim 0.035$ at $10R_\mathrm{S}$), while for higher accretion rates all solutions are thermally stable. It is also shown that in the case of the unstable solutions there always exists a colder thermally stable solution which may describe the actual thermal state of the matter. In principle, occurrence of such 'alternative' solutions does not break the hydrostatic equilibrium, because the flow is dominated by magnetic pressure in the coronal region and therefore it remains unaffected by abrupt change of the density. Although they might correspond to true physical situations, they do not describe a flow with warm optically thick corona, but rather apply to a situations where a cold disk is surrounded by hot and optically thin corona. The thermal instability therefore gives reasonable constraints on occurrence of warm corona in accretion flows.

Large survey of the solutions across the parameter space performed in the rest of the Paper I reveals positive correlation of the corona optical depth, average temperature and Compton y-parameter (all directly measurable from observations) with power released in the disk and the degree of disk magnetization. This suggests that the most prominent warm coronas would be observed from strongly magnetized disks with high accretion rates. The thermal instability further limits a presence of warm corona in the colder, highly magnetized regions. Most likely, warm corona appears in regions of maximal energy dissipation in the innermost parts of the accretion flow ($R \lesssim 10R_S$ for $\dot{m} = 0.05$ and $R \lesssim 60R_S$ for $\dot{m} = 0.5$). This finding in agreement with the fact that SXE is observed only in most luminous accreting sources.

Having determined the vertical structure of the flow, it is easy for the author to estimate the fraction of the heat dissipated in the warm corona region. The calculated values are reaching 0.7 in the most favorable conditions (upper right regions of panels in Fig. 11 of the paper) that correspond to significant dissipation in the corona and only mild dissipation in the disk. Although this does not agree completely with the extreme scenario of passive disk and active corona suggested by observations, it clearly confirms that the work of the author goes in right direction.

Below I list some questions that came to my mind when reading the first paper of the author:

1. When exploring the parameters space, the author sometimes encounters a substantial accretion rates (significant fractions of $\dot{M}_\mathrm{Edd}$). In addition, it is found that high accretion rates are also a favorable condition for the ap-

pearance of the warm corona. As discussed many times in the literature, for so high accretion rates the radial advection of gas internal energy may play an important role. How would the vertical structure change if the author considers additional advection term in his energy-balance equation?

2. This is rather a minor comment: it seems that density is missing on the right-hand sides of equations (15) and (16) of Paper I.

3. Is the single temperature approach sufficient for the hot ionized gas in the warm corona?

4. When describing the vertical structure of the solutions whose part is thermally unstable, the author advocates for a switch to the alternative colder and thermally stable solution in that region. Would it be possible to obtain a global solution that contains this cooler part directly by solving the governing differential equations? In other words would that alternative solution satisfy the governing equations and boundary conditions derived by the author?

5. The work of the author is motivated by the model of Begelman et al. (2015), which is however missing the radiative tranfer. Begelman's model is largely inspired by numerical simulations in most of which the radiation is also missing. Did the author consider comparing his results with the local numerical simulations of Blaes, Krolik, Hirose and Shabaltas (2011, ApJ 733:110) or Krolik, Hirose and Blaes (2007, ApJ 664:1045), where the radiation is included and plays an important role?

Paper II

In Paper II the author applies his model to the case of accreting flows around supermassive black holes in AGNs. Although the problem is governed by the same set of equations, there are two important differences with respect to the situation described in Paper I. Firstly, the radiation pressure represents a large contribution to the total pressure supporting the disk in comparison to the gas pressure. Such flows are known to be unstable with respect to Lightman-Eardley instability. Such instability might cause a blow-up of the solutions with the regions, where the density roughly does not change over a large range of heights. In non-magnetized case, the density profile might by restored by a convection. However, since the convective properties of the magnetized accretion flow are not known and the author essentially neglects all convective motions in his model, the solutions with negative gradient of the density are excluded from his analysis. This typically relates to models with small optical depth of the corona or optically thick models with high accretion rate and low magnetization. Secondly, the author includes a quenching of the disk dynamo activity at heights where magnetic pressure exceeds Pessah & Psaltis (2005) critical value $P_{\mathrm{mag,max}} = [(5/3)P_{\mathrm{gas}} \times \rho(R\Omega)^2]^{1/2}$ by implementing a threshold function. While the influence of this threshold is clearly visible in the profiles of magnetic parameter α_{B}, its impact on the vertical structure might be negligible because a local production of the magnetic field is only small part of the total magnetic heating of the plasma.

The overall structure of the paper is similar to Paper I. At the beginning the author explores in details representative solutions of the vertical structure for three 'canonical' cases of high, intermediate and weak magnetization of the disk. In addition, he also shows vertical profiles of isobaric temperature gradient of the net radiative cooling rate $\mathcal{L}_{\mathrm{rad}}$, whose negative values indicate thermally unstable regions. The gradients are taken either with constant gas pressure as in the 'classical' criterion for the thermal instability, or with constant sum of gas and magnetic pressures. When applying the latter, most of the solutions are thermally stable, the classical condition however puts strong constraints. To decide which criterion applies to stability of warm corona, a time-dependent analysis is needed which is well behind the scope of the paper.

However, In addition to the work presented in Paper I, the author performs much detailed comparison with a large set of available observations. By taking a sample of large amount of randomly generated solutions at fixed radius $R = 6R_{\mathrm{S}}$ with normally distributed black hole masses around $6.8 \times 10^7 M_\odot$ and accretion rate normally distributed around power-law relation between $M - \dot{M}$ that correspond to the sample of unobsured type-I AGNs composed by Jin et al. (2012), he determined the warm-corona optical depths and temperatures and compared them with the values inferred from observations. The predicted values lie within a ranges of temperatures 0.01 to 1 keV and optical thickness $2 - 50$. The sample also contains models with thermally unstable zones where the cut-off of the warm corona to the thermally stable colder solution can be chosen arbitrarily. The observed values agree well with the values predicted by the models. In addition in some cases the observations are near the threshold of thermal instability of the solutions. Since the gas in the unstable regions may undergo evolution on the thermal time scale, it would be nice to develop model further, leaving the assumption of static corona and making predictions about time evolution of these systems.

In the following I again list some questions that crossed my mind when reading the second paper:

1. How significant is the MRI-quenching? Is it important and can one see its effect in the calculated vertical structure?
2. Why fixed radius of $R = 6R_S$ has been imposed for the sample of randomly distributed models and not some other value (e.g. the radius of maximal energy release at $R \approx 4R_S$)?
3. The sample of observed AGNs likely contains also rapidly spinning black holes. Rotating black holes are known to have higher accretion efficiency in comparison to non-rotating ones. The disk is able to reach smaller radii deeper in gravitational field and thus at a fixed radius more energy may be released for the same black-hole mass and accretion rate. How this additional effect of black hole spin would possibly affect the analysis in the paper?

Paper III

Paper III deals with numerical simulations of warm corona using one dimensional radiative transfer code TITAN and Monte-Carlo code NOAR. Contrary to Papers I and II, the use of the numerical codes allows the author to find also spectra of emergent radiation from the warm corona, including the Compton scattering in lines. On the other hand, a slightly different setup is assumed for the warm corona that is now approximated by a constant density slab above the accretion disk with prescribed uniform heating in the vertical direction. The vertical structure of the disk is not simulated, instead its influence is represented by a black-body radiation illuminating the corona from the bottom side. On the other hand, the corona is also irradiated from the top by hard X-ray radiation with power-law spectra representing the hot optically thin corona in the vicinity of accreting black hole. This latter irradiation is missing in the situations considered in Papers I and II.

A highly parameterized setup allows the author to consider also the situation, where the underlying disk is passive. In that case the radiation flux emerging from the corona on the bottom side exactly compensates the incoming flux from the disk to corona. The cases when the flux from the corona exceeds the incoming flux then correspond to a ‘patchy’ corona, when the corona does not surround entire surface of the disk. The boundary condition at the bottom of the corona can be determined using the parameter χ that expresses the fraction of the total power released in the corona to the flux of the emergent radiation and as such it coincides with the parameter f introduced in Paper I and II. While f and the corona optical thickness τ_{cor} were determined by elementary physical processes in the disk-corona system given mostly by the level of magnetization, radius and accretion rate, here both χ and τ_{cor} are treated as free parameters.

The author performs large number of simulations for different values of χ and τ_{cor}. For each simulation he evaluates the fraction of Compton cooling in total cooling process of the corona. The results clearly show that the Compton cooling is the main cooling process. This is particularly true for patchy corona, where the Compton cooling rate exceeds 90% of the total cooling rate. The author also chooses two representative cases of the patchy corona above a passive disk ($\chi = 1.35$) and fully covering corona above the less passive disk ($\chi = 0.753$) for which he shows the vertical temperature profiles, heating/cooling profiles and spectra of emerging radiation. The latter case corresponds to situation where about about 75% of the accretion power is liberated in the corona, still above the maximal values of f found in Paper I and II. When comparing with observations, the conclusion of the paper is that the radiation spectra slightly favours the scenario of patchy corona above the cold passive disk.

Unfortunately, since the properties of corona considered in the paper are different from the vertical structure obtained in Paper II (e.g. uniform heating and density, irradiation from above by hot optically thin corona), it is not easy to decide whether the conclusions of the paper disfavour the results of Papers I and II. In this sense, I would appreciate if the author could put the results of Paper III more to the context of situations considered in Papers I and II.

Below I list a question that I came across when reading the paper:

1. Could the enormous requirements on the fraction of accretion power released in the corona be a consequence of rather idealised setup for warm corona considered in the simulations?
2. Could some differences be attributed to the illumination of the corona from the top that is not considered in the Papers I and II?

In conclusion, let me stress again that I found the level of thesis of Dominik Gronkiewicz very high. The methodology adopted by the author combines expertise in complicated analytic calculations, as well as demanding numerical simulations and clearly demonstrates candidate's huge knowledge of the subject, as well as his great ability to independently conduct scientific work. The long-term effort of the author brought plenty of new, original and interesting results that has been published in three already highly-quoted scientific papers (number of citations according to ADS: Paper I – 29, Paper II – 7, Paper III – 65). The questions I raised in this report should not be by any means regarded as a criticism of the author's work. Some of them go well behind the scope of the thesis and that is why I do not insist on answering all of them at the PhD defense.

Summing up, I consider the doctoral thesis of Dominik Gronkiewicz to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

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