

黑洞热吸积流的理论研究

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活动星系核 (AGN)、低光度活动星系核 (LLAGN) 以及 X 射线双星 (XRB) 系统中都存在黑洞吸积过程. 黑洞吸积是人们理解相关天体的辐射、光变等现象的关键. 本学位论文主要侧重于对目前非常流行的热吸积流 (径移主导吸积流 ADAF 以及明亮热吸积流 LHAF) 的研究. 该类吸积流是理解 LLAGN 以及处于硬态的 XRB 的基本理论模型.

论文第 1 章详细介绍了相关的背景. 首先讨论了天体环境中的黑洞及其所处的系统 — AGN、LLAGN 以及 XRB. 随后, 我们介绍解释上述天体现象的基本物理图像 — 吸积过程. 我们介绍了吸积的基本概念, 并着重讨论了角动量的损失机制、主要的吸积流模型、ADAF 和标准薄盘 (SSD) 间的转化机制等. 此后, 我们详细介绍了本文的重点内容: ADAF 这个几何厚光学薄的热吸积流的基本动力学性质、辐射过程以及其近期的主要进展: 外流、湍动对电子的直接加热以及在较高吸积率下的重要发展 — LHAF. 这方面的讨论是本论文的基础, 也是 15 yr 来吸积理论发展的主要方向.

第 2 章主要探讨了热吸积流中外流对吸积内流的动力学作用. 观测 (典型的, 如银河系中心)、理论研究以及 (磁) 流体的数值模拟等各方面工作表明, 吸积流中的外流现象非常普遍. 但是在研究这个问题时, 尤其是在解释观测数据时, 人们往往只考虑外流带走物质的影响, 而忽略了其他效应 (如角动量的转移). 这显然跟数值模拟的结果不相符合. 我们拓展 Blandford 和 Begelman 的绝热内流 — 外流模型, 研究了外流对吸积流的影响. 我们采用参数化的办法来给出外流的基本物理量. 结果表明: (1) 在目前观测及理论都不明确的情况下, 只考虑外流质量损失的贡献是能接受的, 所得到的参数在误差 2~3 倍范围内是准确的; (2) 如果外流的物理性质跟吸积流有较大不同, 它的动力学作用将不可忽略. 此外, 我们的新方法有利于研究外流自身的动力学及其辐射的贡献.

随后 (第 3~4 章), 我们研究了热吸积流中另外一个重要的物理过程: 康普顿散射. 热吸积流 ADAF 的气体温度高、密度低, 主要辐射过程是同步辐射、韧致辐射以及逆康普顿散射. 在较高吸积率时康普顿散射是气体的主要冷却机制. 然而, 几乎所有以前的工作都基于局部康普顿近似, 即只考虑了吸积流中垂向的辐射转移过程. 很显然, 对 ADAF 而言, 其径向上也同样是光学薄, 而且往往温度差别很大, 因此径向的康普顿散射应该同样非常重要. 我们指出了通常的“局部”康普顿散射的不足, 并首次得到了吸积盘的自洽的动力学结构及辐射谱. 我们发现, 尽管整体康普顿过程的动量转移的作用可以忽略, 但是其能量转移的效应非常显著. 根据所采用的计算康普顿散射过程的方法, 该工作分成两步.

首先, 在第 3 章, 由于径向的辐射转移过程非常复杂, 我们采用简化的辐射模型来计算径向的康普顿散射过程. 结果如下: (1) 吸积流的外区为康普顿致热, 内区为康普顿制冷, 分界半径 $\approx 5 \times 10^3 r_s$, r_s 表示 Schwarzschild 半径; (2) ADAF 的吸积率上限将降低, 但是由于吸积流内区强烈的康普顿致冷效应, 其总的辐射效率将提高; (3) 外区的康普顿致热效应可能会导致 AGN 中吸积流的“振荡”, 即吸积流将处于活动态和非活动态的不断转化中. 处于活动态的时间约等于维里半径处的气体吸积时标, 而处于非活动态的时间约等于维里半径处的气体冷却时标.

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随后在第 4 章, 我们采用严格的 Monte Carlo 数值模拟的方法来统一处理了吸积流中的辐射过程, 进而研究热吸积流的内区的整体康普顿冷却效应的影响. 我们的主要结果跟前面第 3 章的结论是一致的. 此外, 我们还发现, 吸积流的辐射效率有较大的提高, 增大的幅度比前面简化处理的幅度要大; 同时, 辐射谱的谱型也会有所改变. 随后, 我们研究了吸积流中外流对辐射谱的贡献问题. 我们发现外流的温度和柱密度可能有助于解释目前学术界的一大难点 — ADAF 的理论温度和光深跟观测值间有较大偏差. 其次, 我们证实了从前的结果 (Yuan 2001, 2003), 即在较高的吸积率下, ADAF 的内区将热不稳定, 可能变成了 SSD, 或者是处于一种冷热气体共存的两相吸积流的状态, 这正是 LHAF 所预言的结果. 令人遗憾的是, 我们暂时还不能区分这两种情形. 我们认为两相吸积流模式有可能能够解释 XRB 系统中的陡幂率谱态. 这一点还有待于作进一步的探讨.

论文的最后 (第 5 章) 为简单的展望.

Theoretical Researches on Hot Accretion Flows around Black Holes

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Black hole accretion systems, which are widely believed to be harbored in the central regions of active galactic nuclei (AGNs), low-luminosity AGNs (LLAGNs) as well as some X-ray binaries (XRBs), are the key physical processes to understand their observational phenomena, like spectral energy distribution, radiative variability, etc. In this thesis, we focus on the hot accretion flow models, including advection-dominated accretion flow (ADAF) and luminous hot accretion flow (LHAF). These models are the foundations to explain the observations of LLAGNs and XRBs in hard state.

In Chapter 1, a detailed description of the background is presented. First the astrophysical black holes and the systems in which they reside are discussed. Then, an extensive discussion on the accretion process is presented. The basic concepts, 4 well-known accretion models and the mechanism of the transition between ADAF and standard thin disk are focused on. After this, we further describe the properties of ADAF — the basic model of this thesis, e.g., the dynamics, the radiative processes and several recent progresses: outflow, direct turbulent heating to the electrons, as well as LHAF at relatively high accretion rate.

In Chapter 2, the influences of outflow on the dynamics of inflow are explored. As indicated through observations (e.g., towards the Galactic center), theoretical researches and (magneto-) hydrodynamical simulations, outflow is a common phenomenon in accretion systems. However, most researches in this field, especially when aiming at explaining/fitting observational data, incline to only include the mass loss due to the existence of outflow, while all the other effects like the angular momentum transport are totally neglected. This obviously conflicts with the results from simulations. Since outflow is not fully understood currently, we here parameterize its properties. Our results are shown as follows: (1) under current status of observations and theories, it is acceptable to only include its mass loss contribution, the derived properties (e.g., density, temperature) are accurate within a factor of 2~3; (2) outflow's other dynamical influences (angular momentum and/or internal energy

transport) can never be neglected, provided that these highly deviate from those in inflow. Besides, compared with all the previous work, our new approach also has the advantage of its potential applications in exploring the dynamics and radiation of outflow itself.

In Chapter 3 and 4, another important mechanism — Compton scattering — in hot accretion flows is studied. Being tenuous and hot, the main radiative cooling processes in ADAF are synchronization, bremsstrahlung and their inverse Comptonization. The Comptonization will dominate at relatively high accretion rates. We note that almost all the previous works are based on the one-zone approximation, in which only the local Comptonization (in vertical direction) is considered. On the other hand, we note that ADAF is also optically thin in the radial direction, and the gradient of the electron temperature is high, thus the Comptonization in radial direction (global Comptonization) should also be important. It is found that, although the momentum transport due to this global Compton scattering is negligible, its energy transport is significant. Based on the treatment of the Comptonization procedure, we separate our work into two steps.

First in Chapter 3, the global Comptonization effect in hot accretion flows is generally investigated. Due to the complexity in solving the radiative transfer equation in the radial direction, we apply a simplified treatment to calculate the global Compton scattering in the radial direction. The results are: (1) the inner regions of the hot accretion flow are cooled down, while the outer regions are heated up, the dividing radius is approximately $5 \times 10^3 r_s$, where r_s is Schwarzschild radius; (2) the upper limit of accretion rate in ADAF is reduced, while the radiative efficiency should be significantly increased, due to the strong global Compton scattering in hot accretion flows; (3) the global Compton heating effect in the outer regions may cause the “oscillation” of the accretion flow in AGN between active and non-active phases. The duration of the active phase approximately equals to the accretion timescale at the virial radius, while the duration of the non-active phase may be comparable to the cooling timescale at the virial radius.

Subsequently in Chapter 4, the more accurate Monte Carlo simulations are used to uniformly deal with the Compton scattering process and explore the Compton cooling effect in the inner regions ($r \leq 300r_s$) of the hot accretion flows. The results by using this approach are consistent with those in Chapter 3. Besides that, it is found that the radiative efficiency is increased by a factor of 5 at $0.05\dot{M}_{\text{Edd}}$, much higher than the expected; the spectral shape is also modified due to the existence of global Comptonization. We then discuss the contribution of the outflowing material to the observed spectrum. We find that the temperature and column density of outflow can partly help to explain one of the major difficulties in accretion fields, i.e., the temperature and optical depth from observational fittings deviate from what are predicted by ADAF theories. We also confirm the previous analysis (Yuan 2001, 2003) that the inner regions of hot accretion flow is thermally unstable. One consequence is that the flow will collapse to form a thin disk. The other possibility predicted by LHAF is that the hot accretion flow will be filled with cold clumps/clouds. Disappointedly, we cannot rule out any of these two possibilities at present. The latter, namely two-phase accretion mode, could explain the steep power-law state in XRBs.

In Chapter 5, a brief discussion of conceived researches related to this thesis is presented.