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博士论文摘要选登

黑洞吸积盘的数值模拟

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摘 要： 近十几年来，人们已经对吸积盘进行了深入的研究。前人很多工作都是解析工作。虽然解析工作能够简单明了地揭示盘的许多重要性质，但吸积盘的很多重要性质 (例如：对流和外流) 没有办法通过解析工作进行深入的研究。数值模拟是研究天体物理的重要手段。近十年来，随着计算机技术的迅速发展，数值模拟在天体物理研究中扮演了越来越重要的角色。本论文主要用数值模拟的手段研究吸积盘中一些重要的物理过程。

第 1 章首先介绍了黑洞吸积盘所处的环境——活动星系核和黑洞 X 射线双星。随后我们简单介绍了几种主要的吸积模式。径移主导的吸积流和明亮热吸积流 (LHAF) 是本论文的基础。我们详细介绍了径移主导的吸积流的动力学性质，特别地我们详细介绍了 ADAF 的对流不稳定性。我们还介绍了 ADAF 的辐射。最后，我们介绍了明亮热吸积流的性质。

第 2 章介绍了辐射对热吸积流的性质的影响。研究 ADAF 的数值模拟的一个重要发现是 ADAF 是对流不稳定的。对流导致在吸积盘外边界被吸积的物质最终只有少部分落入中央黑洞，其余的形成对流的旋涡。这导致吸积率随着吸积的进行逐渐降低。吸积率随半径的变化对于我们解释观测到的辐射特别重要。其次它还决定着黑洞的增长以及黑洞自旋的演化。以前的关于热吸积流的数值模拟都没有考虑辐射效应。然而，在高吸积率下，辐射非常重要。因此，我们在第 2 章中研究了高吸积率热吸积流 (LHAF) 的对流不稳定性问题。我们的研究发现，对于 LHAF，虽然辐射制冷大于粘滞产热，但吸积流仍是对流不稳定的。吸积率随着吸积的进行仍然降低。

对于稀薄的等离子体，电子的平均自由程远大于其回旋半径，热传导是沿着磁力线方向的。当温度在引力方向升高，等离子体是磁热不稳定的 (Magnetothermal instability, MTI)。MTI 可以放大磁场，并使磁力线沿着温度梯度方向。对于吸积率低的 ADAF，气体非常稀薄，吸积流应该是磁热不稳定的。此外，吸积流也是磁旋转不稳定的 (Magnetorotational instability，MRI)。因此，在低吸积率的吸积流中 MTI 和 MRI 共存。我们在第 3 章中研究了吸积流中的 MRI 和 MTI，发现 MTI 可以将径向磁场和环向磁场放大约 10 倍，而 MRI 只是将环向磁场放大约 10 倍。我们发现当两种不稳定性都存在时，磁场被放大的倍数是它们单独存在时放大倍数的乘积。粘滞的本质是磁应力，考虑 MTI 后，由于 MTI 对磁场的放大，磁

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应力也随着增大，粘滞增强。结果显示考虑 MTI 后，粘滞增强 10 倍多。最后我们发现 MTI 引起的湍动可以转移角动量。由于我们的初始磁场太弱，因此在模型中雷诺应力占主导。

在第 4 章我们用自相似的方法讨论了吸积流的外流以及大尺度磁场对内流的影响。前人关于 ADAF 的解析工作考虑外流对吸积流的影响时，只是简单地假设吸积率是半径的函数，而没有考虑外流对吸积流的角动量以及能量的影响。而当外流的比角动量与内流不同时，外流就会带走或者留下角动量。当外流的比内能与内流不同时，外流也会加热内流或使内流冷却。此外，我们还考虑了大尺度磁场对吸积流的影响。

论文的最后 (第 5 章) 为简单的展望。

Numerical Simulation of Black Hole Accretion Disks

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Abstract: Accretion disks have been investigated intensively these years. A large fraction of previous works analytically investigate the disk properties. Analytical method is very simple. But it can not investigate some important properties of accretion disks such as convection and outflow. Simulations is very important for astrophysical research. With the development of computer science, simulations become more and more important. In this thesis, we mainly use simulations to investigate some important process in accretion disks. In Chap. 1, we first briefly introduce the circumstance in which black hole accretion system resides. Advection-dominated accretion flow and luminous hot accretion flow (LHAF) are basis of this thesis. We introduce the dynamical properties of ADAF, especially the convective instability in ADAF. Then we introduce the radiation of ADAF. Finally, we briefly introduce the properties of LHAF. In Chap. 2, we investigate the effects of radiation on the properties of hot accretion flow. The important finding of previous simulations of hot accretion flow is that ADAF is convectively unstable. Only a small fraction of the gas captured by accretion flow at outer boundary can finally fall onto the black hole, the rest circulates in convective eddies. Accretion rate decreases with decreasing radius. The accretion rate profile has important implications for the radiation we observed. Accretion rate profile also determines the growth of black hole and the evolution of black hole spin. The previous simulations of hot accretion flow did not consider radiation at all. In reality, radiation is very important when accretion rate is high. We investigate the convective instability of high accretion rate hot accretion flow (LHAF) in Chap. 2. We find LHAFs

is still convectively unstable, although radiation cooling rate is bigger than viscous heating rate. For LHAF, accretion rate also decreases with decreasing radius. For dilute plasma with electron mean free path much larger than gyroradius, thermal conduction is important and along magnetic field lines. When temperature increases in the direction of gravity, the plasma subjects to magnetothermal instability (MTI). MTI can amplify magnetic field and make field lines align with temperature gradient. For ADAF, the accretion rate is very low and the gas density is very small. Thus, MTI should exist in ADAF. In addition, magnetorotational instability (MRI) exists in accretion flow. We investigate MTI and MRI in accretion flow. We find both the radial component and the toroidal component of the field can be amplified by a factor of 10 by MTI. MRI only amplifies the toroidal component by a factor of 10. In principle, viscosity is Maxwell stress. When MTI amplifies magnetic field, viscosity is enhanced by a factor of 10. We find MTI induced Reynolds stress can transport angular momentum. In Chap. 4, we investigate the influence of outflow and large scale magnetic field on the dynamics of inflow in self-similar approach. In previous works, when consider outflow, they just simply assume accretion rate is a function of radius. When the specific angular momentum of outflow is different from that of inflow, outflow will take away or deposit angular momentum. When the specific internal energy of outflow is different from that of inflow, outflow will heat or cool inflow. We also take into account the effects of large scale magnetic field. We present in Chap. 5 a very brief discussion of conceived future researches related to this thesis.