博士学位论文摘要选登

星系中心超大质量黑洞的自转

李彦荣 †

(中国科学院高能物理研究所 北京 100049)

自转作为描述黑洞天体物理性质的两个基本参数之一，其研究正方兴未艾．本文以星系中心超大质量黑洞 (SMBH) 的自转为研究主题，阐述自转的确定、宇宙学演化及其对黑洞吸积历史的限制．

SMBH 附近的加速机制使粒子产生甚高能量的辐射，对这些辐射的观测可以给出中心黑洞的信息．基于此，我们提出了利用 TeV 光变限制黑洞自转参数的方法．基本原理是： TeV 光变给出了辐射区域最大尺度的限制，吸积盘辐射场通过对 TeV 光子的吸收光深给出了辐射区域最小尺度的限制．由于吸积盘辐射场与黑洞自转直接相关，从而结合 TeV 光变可以限制黑洞自转．对于给定的光度，快速自转黑洞吸积盘的辐射区域相比不转黑洞的更加致密．因此，快速自转黑洞更有利于 TeV 光子逃逸出吸积盘的辐射场．我们将这个方法应用到星系 M87, 其核区探测到 $1 \sim 2$ d 的 TeV 快速光变．为此，我们首先在 Newton 时空下利用 RIAF 的自相似解计算了 10 TeV 光子的光深，发现只有快速自转 ($a > 0.65$) 的黑洞才能使得辐射场对 TeV 光子透明．然后在广义相对论时空下求解了 RIAF 结构和出射谱，光深计算的结果同样表明 M87 中心的黑洞在快速自转．这个方法可以应用到低光度活动星系核中．

基于 Sołtan 理论，我们建立了描述辐射效率宇宙学演化的 $\eta-$ 方程，它把辐射效率与活动星系核 (AGN) 光度密度、黑洞质量密度和 AGN 的间歇参量联系起来．将这个方程应用到巡天数据，我们发现辐射效率从 $z \approx 2$ 时的 $\eta \approx 0.3$ 减小到 $z \approx 0$ 时的 $\eta \approx 0.03$．这个演化趋势直接说明黑洞在随红移减小而自转减慢，从而给出了间歇式随机吸积可能主导黑洞质量增长 ($z \approx 0 \sim 2$) 的证据．

为了理解不同质量黑洞自转的演化，我们推导了辐射效率演化的广义 $\eta-$ 方程．我们首先利用最新的星系光度函数，计算了星系中心 SMBH 的质量函数，然后结合观测的 Eddington 因子和活动星系核光度函数，得到了辐射效率与质量和红移的关系．不同质量黑洞辐射效率演化不同，暗示着黑洞自转的演化可能依赖于质量 (downsizing 现象)．

利用星系并合触发黑洞活动的假设，我们计算了 AGN 光度函数． EPS 理论结合黑洞质量与暗物质晕质量的相关关系给出了黑洞的并合率，星系光度函数给出了黑洞的数密度．对不同质量比的并合积分给出了 AGN 光度函数．为了拟合观测，我们发现并合质量比存在红移的演化：星系小并合在低红移占主导，而主并合可能在高红移 ($z \approx 2$) 占主导．结合得到的黑洞自转演化，这说明星系小并合可能是随机吸积的触发机制之一．

最后我们总结了本文完成的主要工作及其对其他领域的影响，并简要地展望了未来亟待解决的重大问题．

†2010-07-10 获得博士学位，导师：高能物理研究所王建民研究员； liyanrong@mail.ihep.ac.cn

Spins of Supermassive Black Holes in Galactic Centers

LI Yan-rong
(*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049*)

As an essential parameter describing supermassive black holes (SMBHs), spin remains an unresolved issue in black hole astrophysics. This thesis is focusing on the study of spins, including how to estimate the spin of an individual SMBH, the cosmological evolution of SMBH spins, and its constraints imposed on the black hole accretion history.

We propose a new method to constrain the SMBH spins using the TeV flux variability. The underlying principle lies at the fact that the TeV flux variability places a limit on the maximum size of the emission region, while the absorption optical depth of the radiation fields from the accretion disk to the TeV photons places a limit on the minimum size. Since the radiation fields are governed by the SMBH spins, combining these two factors can constrain the spin parameters. We apply this method to the radio galaxy M87. In its central region, the fast TeV flux variability with a time scale of 1 to 2 days is detected. We firstly calculate the optical depth to the 10 TeV photons using the self-similar solution of RIAFs in the Newtonian time-space. We find that only for the fast spinning holes ($a > 0.65$) the radiation fields do become transparent to the 10 TeV photons. Then we numerically solve the full equations of general relativistic RIAFs. The resultant optical depth confirms that the central SMBH in M87 is spinning rapidly. This method can be applied to the M87-like low luminosity active galactic nuclei (AGNs).

Based on the Sołtan argument, we construct an η-equation to describe the cosmological evolution of the radiative efficiency η for the SMBH accretion. This equation links η with the AGN luminosity density, the SMBH mass density, and the duty cycle of AGNs. Applying it to the existing AGN and galaxy survey data, we find that η decreases by an order of magnitude from $\eta \approx 0.3$ at $z \approx 2$ to $\eta \approx 0.03$ by $z \approx 0$. Such an evolutionary trend implies that the SMBHs are spinning down with cosmic time, which can be attributed to the episodic and random accretion.

In order to explore the mass-dependent spin evolution, we then derive a generalized η-equation. Our results show that the SMBH spins may be downsizing.

Using the hypothesis that the AGN activity is triggered by the galaxy mergers, we calculate the AGN LFs (luminosity functions) by manipulating the observed galaxy LFs and the theoretical merger rates from the EPS theory. We find that our model reproduces the observed AGN LFs, provided that the mass ratio of the merging galaxies changes with cosmic time. The results show that minor mergers are important in triggering AGNs at low redshfits, while major mergers may dominate at high redshifts. Regarding the spin evolution of SMBHs, we suggest that minor mergers of galaxies may constitute one of the triggering mechanisms for random accretion.

Lastly, we give a summary of our works, the potential impacts on other subjects, and a brief outlook for the future important problems.