第 51 卷 第 3 期 天 文 学 报 Vol.51 No.3
2010 年 7 月 ACTA ASTRONOMICA SINICA Jul., 2010

博士学位论文摘要选登

大质量黑洞及其寄主星系的共同演化

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类星体寄主星系的观测结果以及星系核球与黑洞质量间的密切相关，清晰地给出一幅星系和黑洞共同演化的图像. 如何描绘出这幅图像，有大量未解决的问题，其中不乏基本问题. 本文努力构建这幅美妙的图像，内容覆盖了种子黑洞的形成、大质量黑洞的自旋和负载循环的宇宙学演化、星系的恒星形成率随质量和红移的演化以及星暴和黑洞活动的相互作用.

我们首先总结了自 Magorrian 关系发现 10 余年来的主要研究进展，归纳出了星系和黑洞研究的热点问题及其状况，确定了几个重要问题作为本学位论文的主攻方向. 它们是：(1) 原初黑洞快速增长的辐射反馈； (2) 如何描述黑洞与星系的共同增长？ (3) 控制共同演化的机制是什么？ (4) 在 kpc 的尺度上，星系如何向黑洞提供吸积原料？

已有理论指出原初黑洞的快速增长，可能是一种形成大质量黑洞的有效途径，甚至可以通过中微子冷却加速原初黑洞的增长. 我们考虑了以 Compton 加热为主的辐射反馈机制，发现原初黑洞只能以百分之几的 Eddington 吸积率增长，实际上增长很慢，而且吸积也可能是间歇式的. 这个结论被 Milosavljevic 等的数值模拟所证实. 重子物质快速吸积方式的困难使得原初黑洞增长的问题更加突出.

我们发展了一套基于 Soltan 假设的计算黑洞负载循环的有效公式. 通常负载循环定义为活动的黑洞与总黑洞的数密度之比，等价于活动时间占总时间之比. 我们证明了它也等价于活动黑洞的质量密度与总黑洞密度之比. 这个公式不仅可以使我们摆脱关于 Eddington 比宇宙学演化的假设，更为重要的是，可使我们建立黑洞与星系共同演化的统计方程，即 η- 方程. 当我们把这两个新方程应用于 SDSS (Sloan Digital Sky Survey) 以及其它相关巡天数据后，发现： (1) 较低红移 $z < 2$ 时，负载循环的宇宙学演化与恒星形成率密度的演化趋势非常相似； (2) 高红移时，两者演化趋势正好相反； (3) 黑洞的辐射效率具有强烈的宇宙学演化，从 $z = 2$ 时的 $\eta \approx 0.3$ 快速演化到本地宇宙中的 $\eta \approx 0.05$, 这个结果向我们展示了一幅黑洞随机吸积的演化历史.

在第 3 章中我们发展了一套用静止系中 3 750～4 150 Å波长范围内一系列的 Balmer 吸收线估计 SSFR (specific star formation rate, 定义为星系的恒星形成率与其恒星质量的比值) 的新方法. 发现高红移处，从吸收线得到的 SSFR 比由其它指示器，如发射线得到的低 $10^{0.3}$～$10^{0.4}$, 这一结果在一定程度上暗示着初始质量函数随红移有演化，而且高红移处倾向于形成更多的大质量恒星.

为了研究恒星形成与黑洞活动之间的关系，我们首先分析了本地宇宙中约 50 个 Seyfert 星系的恒星形成率，结果表明恒星形成远低于正常星系中 Kennicutt-Schmidt 定律所给出的值，清楚地再现了恒星形成受到黑洞活动的抑制作用. 之后我们从 SDSS 数据中建立了一个含 10 848 个源的 II 型活动星系核样本，红移范围为 $0.03 \le z \le 0.08$, 这使得我们可以测量 ~ 1 kpc 尺度上的恒星形成. 利用简单星族合成的方法 (BC03), 我们发现黑洞的 Eddington 比 λ 强烈依赖于 SSFR, 即 $\lambda \propto \mathrm{SSFR}^{1.5}$. 这个非线性的依赖关系实际上强调了恒星形成对触发黑洞活动的作用，对此我们建立了一个物理模型，

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其中恒星形成中的超新星爆发激发湍动粘滞，从而有效地转移角动量，大量气体流向中心供给黑洞，触发它的活动．这个物理模型正好可以解释当前的统计结果．这些结果表明：一方面，黑洞活动对星系的恒星形成起了抑制作用；另一方面，星系中的超新星爆发激发了足够强的湍动粘滞，可以有效地转移角动量，在向黑洞提供吸积原料的过程中起了至关重要的作用．星系与黑洞是一个自我调节的复杂系统．

最后，我们总结了本学位论文的结果，并展望了以后几年的工作计划．我们认为现阶段该领域内问题多于结论，正处于蓬勃发展时期．

Co-evolution of Massive Black Holes and Their Host Galaxies

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A scenario of co-evolution of supermassive black holes (SMBHs) and galaxies has been clearly conducted by the important evidence from observational results of quasar host galaxies and the relation between spheroid and SMBH mass. There are a plenty of unresolved problems and questions, some being basic, to be addressed in this scenario. The main goal of the present thesis is focusing on the mysterious scenario including growth of primordial black holes, cosmological evolution of spins and duty cycle of SMBHs, and interaction between the SMBH activity and star formation in galaxies from low to high redshifts.

We review the main progress of this field over the past decade since the discovery of Magorrian relation and present comments on some questions in light of our view of points. The key questions to be addressed in this thesis work are: (1) how does the fast growth of primordial black holes influence their evolution? (2) what is the equation to describe the co-evolution of SMBHs and galaxies? (3) what is the mechanism to control the co-evolution? (4) how to transport the fueling gas from kpc scale to the center?

It has been suggested that fast growth of primordial black holes via super-Eddington accretion is a promising way to form SMBHs in high redshift universe. Neutrino cooling has been employed and expedites the growth. We consider the Compton heating of the surroundings of the primordial black holes. We find that the realistic accretion rate is only a few percent of the Eddington rate, and the accretion is episodic. It implies that the fast growth via super-Eddington is not feasible. These conclusions have been confirmed by the detailed numerical simulations of Milosavljevic et al. (2008). The difficulties of the fast growth via accretion of baryon particles make the formation of SMBHs elusive in high redshift universe.

We developed a new formulation to calculate the duty cycle of SMBHs based on the Soltan argument. We show it can be expressed by the mass density ratio of active SMBHs to the total. This not only makes the calculation of the duty cycle independent of the assumption of cosmological evolution of Eddington ratios, but also allows us to set a totally new equation — the so-called η-equation to describe the co-evolution of SMBHs and galaxies. Applying the equations to SDSS (Sloan Digital Sky Survey) and other related survey data, we find that: (1) cosmological evolution of the duty cycle tightly follows the history of star

formation rate (SFR) density in $z < 2$ universe; (2) they just show opposite trends in higher redshift universe; (3) the radiative efficiency dramatically decreases with z, showing $\eta \approx 0.3$ at $z = 2$ and down to $\eta \approx 0.05$ at $z = 0$. It shows for the first time a history of random accretion of SMBH growth from high to low redshift universe.

Chapter 3 is devoted to develop a new method to estimate the specific star formation rates (SSFR) for DEEP2 data. Using the series of Balmer absorption lines in rest-frame 3 750∼4 150 Å, we develop a new method to estimate the SSFR. Applying this new method to both SDSS and DEEP2 data, we find the SSFR derived from Balmer absorption lines is consistent with that from emission lines at local universe, while there is a $10^{0.3}$∼$10^{0.4}$ discrepancy at $z \approx 1$. This result implies the initial mass function changes with redshift, and it tends to form more massive stars at higher redshift.

We pay much attention to the interaction between AGN and star formation in Chapter 4 through investigations of the Seyfert galaxies and type II AGNs. We obtain the SFR in about 50 Seyfert galaxies and compare with the SFR predicted by Kennicutt-Schmidt's law. We find that they are lower than the predicted by a factor of 10∼100, clearly showing the evidence of suppressing the star formation in the 100 pc region around nuclei. 10 848 type II AGNs are selected from SDSS data for the study of starburst and AGN connection. We find the young stars are playing an important role in triggering SMBH activities. A very tight correlation $\lambda \propto \mathrm{SSFR}^{1.5}$ between the Eddington ratio λ and SSFR has been found in the sample. This nonlinear relation stresses the role of supernova explosion, which could excite strong turbulent viscosity to transport the angular momentum of the fueling gas to the SMBHs. We set up a modified model by including the role of supernova explosion to account for the starburst-AGN connection. Indeed, we find that the model can be nicely consistent with the correlation.

In this thesis, we demonstrate a self-adjusted system of galaxies and SMBHs—the SMBHs are triggered via star formation, which would get suppressed by SMBH activities. As a summary of the present thesis, we draw a conclusion that we poorly understand the issues as to formation of SMBHs, evolution of galaxies and SMBHs. There are a plenty of issues to be addressed in future. The solved questions are much less than the bringing out ones.