



活动星系核：炼金炉与引力波辐射

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摘要 在理论上, 超大质量黑洞(supermassive black holes, SMBH)周围的吸积盘在外区具有复杂结构, 其中自引力将不可避免地导致恒星形成; 在观测上, 类星体金属丰度测量和引力波探测显示在活动星系核(active galactic nuclei, AGN) 中心区域存在大质量恒星形成与演化. AGN盘上的恒星及致密天体通常具有很高的吸积率, 以至于这些天体命运发生重大变化, 我们统称为“吸积致变恒星”(accretion-modified star, AMS), 由此形成了一个理论问题和观测效应十分丰富的崭新领域. 研究表明, AGN 盘上的AMS星族会通过吸积快速演化, 最终以大质量恒星为主导, 且在大质量端堆积或截断堆积式分布. AMS死亡后可产生恒星级黑洞, 形成围绕SMBH的卫星黑洞群. 在标准盘上的恒星级黑洞通常会发生Bondi爆炸, 该爆炸的非热辐射峰值在X-射线和伽马射线波段, 热辐射光度可以达到 $\sim 10^{44} \text{ erg s}^{-1}$. 吸积盘上的黑洞在迁移过程中可形成双黑洞, 与周围气体的相互作用可能会加速并合过程, 同时为解释大质量黑洞并合事件提供契机. 此外, AMS模型可合理解释银河系中心的恒星盘和金属丰度, 其中质量为 $40 M_{\odot}$ 的卫星黑洞可解释红外闪烁周期和耀斑轨迹等现象, 这可能是距地球最近的EMRI (extreme mass ratio inspiral)天体. 未来, 更多的引力波探测与光谱光变观测计划相结合, 有望更好地回答AGN盘上恒星及致密天体的演化与并合问题.

关键词 活动星系核, 超大质量黑洞, 吸积盘, 引力波

人们已经广泛接受超大质量黑洞(supermassive black hole, SMBH)吸积产生强烈辐射作为活动星系核(active galactic nuclei, AGNs)能量来源的标准模型^[1]. 该模型强调了SMBH在AGN中的枢纽作用, 但有许多相关问题, 例如如何触发SMBH的吸积及其后续演化过程, 迄今为止, 还没有得到充分的理解. 这其中一个长期的问题是: 宽发射线光谱揭示的吸积与SMBH中心区域的化学演化之间是否存在不可避免的联系. 近年来, 观测的拟合结果显示, 银河系中心存在以大质量恒星为主导(top-heavy)的恒星盘^[2,3], 这为理解银河

系中SMBH周围的恒星形成历史提供了发人深省的线索. 实际上, 自20世纪80年代以来, 便开始有理论研究论证在AGN盘上的恒星形成, 并认为该星族会快速演化为top-heavy形式^[4~11]. Cheng和Wang^[12]从类星体金属丰度出发, 最先意识到AGN吸积盘中可能存在致密天体, 它们之间并合同时产生 γ 射线爆发(gamma ray burst, GRB)以及引力波辐射. 目前, 已经出现诸多相关的观测证据支持这一猜想, 例如GRB 191019A^[13,14].

经过30余年的观测积累, AGN金属丰度的超太阳丰度及无宇宙学演化特征已基本成为共识^[15~17]. 其

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中最引人注意的是[Fe/Mg]丰度比的无宇宙学演化现象^[17~19]. 近年来, 随着对高红移类星体的探测, 特别是JWST运行以来, 人们发现高红移类星体中仍可发射出与本地宇宙AGN中类似的强烈铁发射线^[20~22]. 这与传统化学演化模型对AGN中铁元素的红移演化的预期相悖^[23]. 此外, 尽管有所争议^[24], AGN紫外发射线线强比表明金属丰度与紫外光度^[17]、爱丁顿比^[25]及SMBH质量^[26]之间极可能存在相关性. 而对极邻近Seyfert星系的空间分辨观测显示其 ~ 10 pc范围内的环核区曾在几十兆年前发生过星暴^[27,28]. 同时, 亦有研究发现了AGN中存在超新星的潜在证据^[29,30]. 这都指向AGN盘上的恒星形成与演化问题.

随着引力波时代的到来, 有证据显示AGN吸积盘中可能存在致密天体. 2019年5月21日, LIGO探测到由质量比典型恒星级黑洞(stellar-mass black hole, SMBH)更重的双黑洞并合引起的引力波事件GW190521^[31]. 次年, Graham等人^[32]利用Zwicky Transient Facility (ZTF)的观测数据发现该并合事件的电磁对应体候选者为AGN, 虽然这两者间的潜在联系仍有争议^[33~35]. 此后, Graham等人^[36]又报道了LIGO/Virgo在O3运行期间探测到的9个双黑洞并合的电磁对应体候选者. Li等人^[37]亦发现一些引力波事件可能源于AGN吸积盘中的双黑洞并合. 此外, 有证据显示数个伽马射线暴可能发生在AGN吸积盘上^[13,14,38]. 这些发现使得AGN盘上恒星及致密天体的相关问题一跃成为热点领域. 若未来确认LIGO探测到的某些引力波事件与AGN中的瞬变事件成协, 这将为深入理解AGN金属生成问题^[39~43]做出重要贡献.

本文将AGN盘上的恒星、白矮星、中子星和SMBH统称为“吸积致变恒星”(accretion-modified star, AMS), 即在致密的AGN盘中因不断吸积而快速增长, 导致演化路径发生剧烈变化的天体. 目前已有研究者使用MESA研究AGN盘上单个恒星的演化过程, 内容包括对AGN环境的依赖性、如何脱离主序、金属元素生成等^[44~47]. 但对于这些恒星在AGN盘中作为一个星族的质量函数及金属丰度演化过程, 后续产生的致密天体如何与周围吸积盘气体相互作用, 以及相应的观测特征和应用, 目前还鲜有研究. 因此, 本文将聚焦AGN盘上AMS星族演化、金属丰度演化、SMBH与周围气体相互作用过程、双SMBH并合及AMS模型的

应用展开研究.

1 星族演化与金属丰度演化

AGN无宇宙学演化的金属丰度及铁元素生成问题可由以下假设自然解释: SMBH活动是间歇式的^[48~50], 并且在每次活动期间($\sim 10^8$ yr)都会吞噬活动期间产生的金属^[49,51]. 在该图像下, AGN盘上的化学演化将独立于其宿主星系, 导致其金属丰度不显示出红移演化. 同时, AGN盘上会形成top-heavy形式的恒星盘^[52], 使得高红移类星体可以高效生成铁元素, 而不必依赖于Ia型超新星^[20]. JWST观测到的具有极强或极弱铁发射线的类星体也可由SMBH的间歇式活动解释. 此外, 自引力盘的范围与宽线区一致^[8,53~59], 这又为定量解释金属丰度与SMBH质量、吸积率和光度之间的关系提供了可能性^[39~41].

考虑到恒星质量快速变化, 在“质量空间”中的连续性方程可以用来描述恒星星族演化. Wang等人^[42]采用该方程描述AGN盘上AMS星族的质量函数 $\Psi(m_*, t)$ 演化过程, 即

$$\frac{\partial}{\partial t} \Psi(m_*, t) + \frac{\partial}{\partial m_*} [\dot{m}_* \Psi(m_*, t)] = -\dot{R}_{\text{SN}}(m_*, t) + \dot{S}_{\text{AD}}(m_*, t), \quad (1)$$

其中 $\dot{m}_*$ 、 $\dot{R}_{\text{SN}}$ 、 $\dot{S}_{\text{AD}}(m_*, t)$ 分别代表恒星同时经历吸积与星风损失而产生的净增长率、超新星爆发率(采取连续性方程的一阶近似)以及自引力盘中的恒星形成率(同时包含对核区星团中恒星的捕获率). 该过程由AGN盘中恒星吸积而驱动的AMS演化(加速演化与超新星爆炸)、辐射压驱动的星风、形成于AGN盘中的恒星或从核区星团中捕获的恒星三个因素主导. 此计算聚焦于处于半径 $10^5 R_g$ 范围内的AMS星族在一次AGN活动时间($t_{\text{AGN}} \approx 10^6 \sim 10^8$ yr)内的质量函数及金属丰度演化过程(图1(a)).

AMS主要在赤道面从AGN盘中吸积气体, 在极区通过星风损失质量, 其净增长率为

$$\dot{m}_* = \dot{m}_{\text{ac}} - \dot{m}_{\text{w}}, \quad (2)$$

其中 $\dot{m}_{\text{ac}}$ 和 $\dot{m}_{\text{w}}$ 分别代表AMS吸积率和星风质量损失率. 值得注意的是, 由于AGN盘非常稠密, 故大质量恒星会

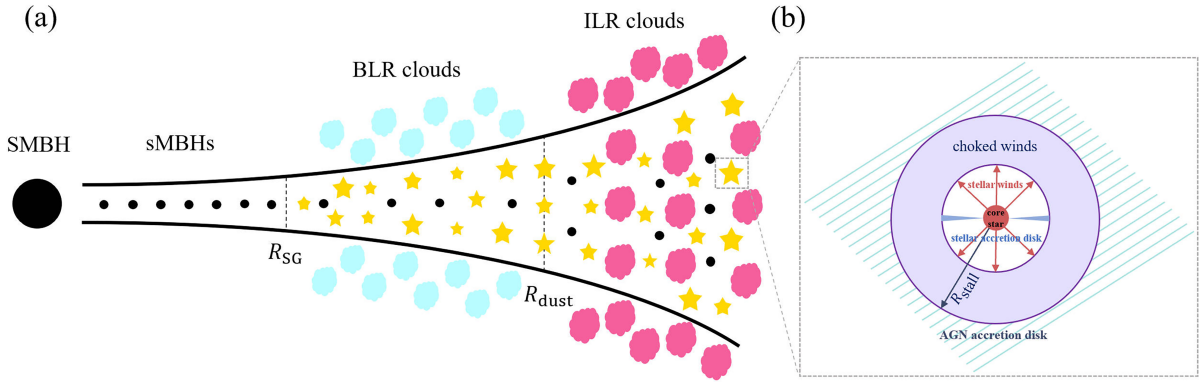


图 1 (网络版彩色)(a) pc 尺度环核区的全局图像。 R_{SG} 为自引力半径, R_{dust} 为尘埃颗粒的升华半径。黑点代表 sMBH, * 代表恒星, 其大小与恒星质量成正比。观测到的发射线光谱包含两个不同宽度的成分, 分别来自宽线区(broad-line region, BLR)和中线区(intermediate-line region, ILR; 大于 R_{dust})。CNR 是由吸积的 sMBH、恒星和超新星组成的复杂环境, sMBH 和恒星都会吸积 AGN 盘内的气体。(b) AGN 吸积盘中形成的 AMS 的特征结构。AGN 盘非常致密, 以至于恒星星风被阻塞, 形成了一个巨大的包层。但包层会再受恒星引力作用而返回到恒星上, 并触发氢燃烧。由于 AMS 数密度很高, 它们的包层可能会产生重叠, 变成团状

Figure 1 (Color online) (a) The global scenario of parsec-scale circumnuclear regions. R_{SG} is the self-gravitating radius, and R_{dust} is the sublimating radius of dust particles. The black dots represent sMBHs, * symbols are accreting stars, and their sizes indicate magnitudes of mass. The observed emission line spectra comprise two components with varying widths originating from the BLR and ILR. The circumnuclear region is a complex environment consisting of accreting SMBHs, stars, and SNe. Both sMBHs and stars are accreting gas from the AGN disk. (b) Characteristic structure of AMSs formed in AGN accretion disks. The AGN disk is so dense that the stellar winds of the host stars are choked, forming a massive envelope. However, the envelope may be gravitationally pulled back onto the stars and trigger hydrogen burning. Due to the high number density of AMSs, their envelopes can overlap and become clumpy

出现受阻星风(choked stellar winds). 关于大质量恒星的受阻星风的想法可以追溯到Shull^[60], 他认为快速的星风会因辐射损失而削弱, 并会根据周围的环境和辐射在某处停滞. 结合AGN 盘环境的近似估算表明, 快速星风会通过辐射冷却迅速热化并停留在某处, 这便是“受阻星风”. 这种特殊星风将有效地减少星风导致的质量损失, 使高金属丰度的大质量恒星、甚至极大质量恒星仍能够有效产生金属. 图1(b)展示了存在受阻星风的AMS结构: 致密的AGN盘将会阻塞星风, 被阻塞的星风逐渐积累, 在恒星核心的周围形成一个极大的包层; 一旦包层积累足够物质, 它可能会被加热到氢开始燃烧的温度, 同时部分气体在引力作用下落回核心, 增加核心的质量. 回落率可能取决于AGN盘密度和恒星质量, 而AMS包层的重叠可能会导致形成团块, 从而加剧回落率的不确定性.

AMS星族的质量函数演化计算表明, 该演化对初始质量函数(initial mass function, IMF)的形式不敏感, 最终会呈现为top-heavy形式(图2(a)~(d)). $\dot{m}_{\text{ac}}^0$ (表征AMS吸积速率)增加会导致质量函数向高质量端加速演化, 这将间接提高超新星爆发率, 从而导致AGN盘中AMS数量减少而sMBH数量增加. β (表征环境对恒

星吸积的抑制能力)可控制AMS最大质量, 导致质量函数在最大质量附近堆积, 从而演变为top-heavy形式. 此堆积效应有利于铁元素的高效产生——质量堆积范围恰好与对不稳定型超新星(pair-instability supernova, PISN)对应的恒星质量范围一致. 当存在星风时, 质量函数会在高质量端出现截断堆积现象——由吸积和星风之间的平衡所决定(图2(e)~(h)). 此截断堆积特征会为PISN的大量集中爆发提供便利. 总之, 在大多数情况下, 大质量恒星的堆积效应是AMS的吸积率、星风、周围环境对其吸积的抑制三方面共同作用的结果, 而较强的星风有利于PISN的集中堆积, 从而导致铁元素的高效产生.

AGN金属丰度(铁和镁元素)的演化同样依赖于AMS吸积率($\dot{m}_{\text{ac}}^0$ 和 β), 且其变化是非单调的(图3). 通常, 铁和镁元素的产量可在几兆年内达到 $10^5 \sim 10^6 M_{\odot}$; 两者的丰度显示出相似的性质, 可达太阳丰度的数倍、甚至数十倍, 这表明或许可通过测量铁和镁的丰度来确定AGN的活动期年龄. 在无星风或弱星风时, $[\text{Fe}/\text{Mg}]$ 丰度比在饱和后处于 $0 \sim 0.2$, 这符合 $[\text{Fe}/\text{Mg}] \leq 0.2$ 的AGN的观测特征, 但低于由SDSS给出的AGN样本所显示的 $[\text{Fe}/\text{Mg}]$ 平均丰度比($0.2 \sim 0.3$).

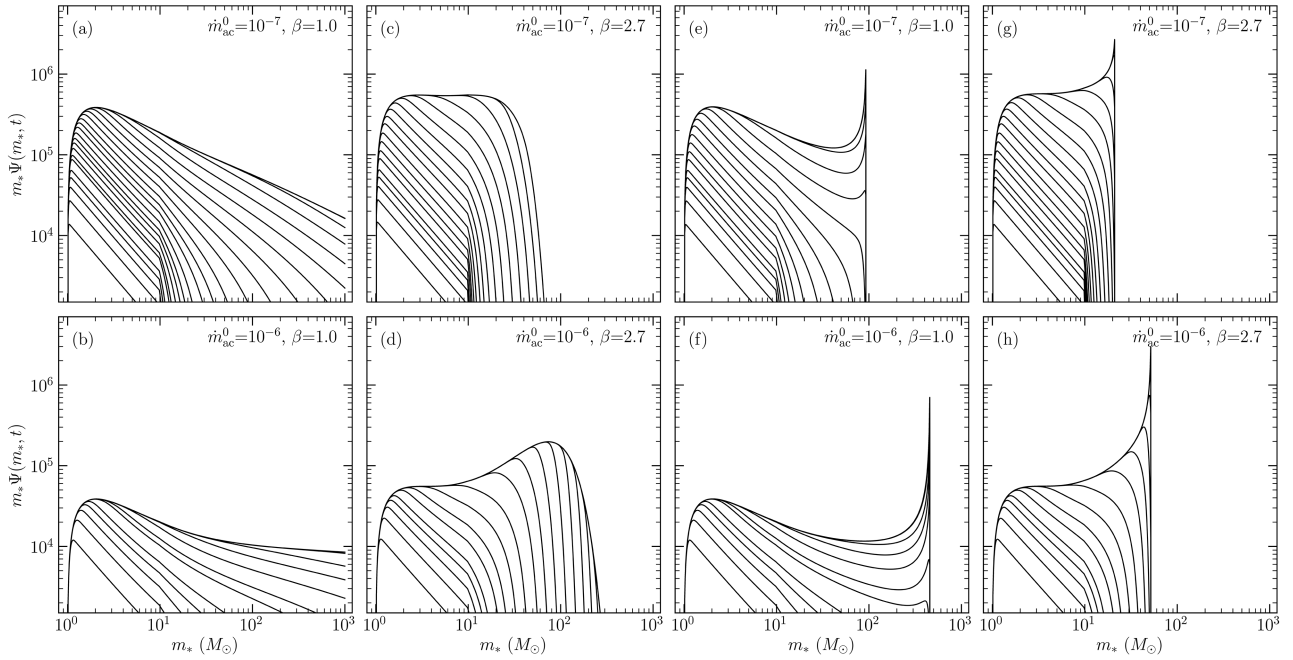


图 2 AMS质量函数的演化过程. (a)~(d) 无星风条件下AMS质量函数的演化. 对给定 $\dot{m}_{ac}^0$, 沿水平从左到右表示 β 增加; 对给定 β , 沿垂直从上到下表示 $\dot{m}_{ac}^0$ 增加. (e)~(h) 强星风 $\dot{m}_w^0 = 10^{-9} M_\odot \text{ yr}^{-1}$ 条件下的AMS质量函数的演化, 子图布局与图(a)~(d)一致

Figure 2 The evolving AMS mass functions. (a)~(d) Evolution of the AMS mass function under no stellar wind conditions. Horizontal rows from left to right with increases of β for a given $\dot{m}_{ac}^0$, and the vertical with increases of $\dot{m}_{ac}^0$ from upper to below. (e)~(h) Evolution of the AMS mass function under high stellar winds of $\dot{m}_w^0 = 10^{-9} M_\odot \text{ yr}^{-1}$, the subplot layout is consistent with the panels (a)~(d)

该问题可通过星风的介入得到解决. 当星风较强时, [Fe/Mg]可超过0.2——截断堆积位置处于PISN范围(140~260 $M_\odot$)内. 值得注意的是, [Fe/Mg]丰度比是结合观测到的Fe II/Mg II线强比与光致电离模型(CLOUDY)计算推算出的^[61], 而前者还依赖于电离源光谱能量分布(spectral energy distribution, SED)、湍流和密度等参数, 故[Fe/Mg]的估算存在较大离散性. 但整体来说, 目前的模型与观测结果基本一致.

2 卫星黑洞群及其观测效应

对于AGN吸积盘中单个AMS的演化, Wang等人^[62]和Liu等人^[63]已针对辐射能谱、光变曲线、外流形成等方面进行了详细计算. 由于SMBH吸积盘气体密度极高($\sim 10^{-10} \text{ g/cm}^3$), 嵌于其中的AMS通常具有很高的吸积率. 如果认为AMS进行Bondi吸积, 那么在考虑吸积盘厚度及中心SMBH潮汐力矩的影响后, 其无量纲的质量吸积率为

$$\dot{M}_s = 1.7 \times 10^7 \alpha_{0.1}^{-4/5} r_3^{-1/10} \dot{M}_p^{3/5} M_8^{1/5} q_5^{-1/3}, \quad (3)$$

其中 $\alpha_{0.1} = \alpha/0.1$ 是黏滞参数, $r_3 = R/10^3 R_g$ 是AMS在吸积盘中的位置半径, $\dot{M}_p$ 是SMBH无量纲的质量吸积率, $M_8 = M_p/10^8 M_\odot$ 是SMBH质量, $q_5 = q/10^{-5}$, $q = M_s/M_p$ 是sSMBH与SMBH的质量比. 该吸积率比通常的超爱丁顿吸积还高出几个量级. 通常, 作开普勒运动的SMBH吸积盘具有较差速度^[64], 这会导致Bondi吸积的物质掉落到靠近sSMBH附近的区域时形成一个小的sSMBH吸积盘, 并在黏滞的作用下向外转移角动量, 释放出大量引力能

$$L_{\text{out}} = 2.2 \times 10^{44} \eta_4 \alpha_{0.1}^{-4/5} r_3^{-1/10} \dot{M}_p^{3/5} M_8^{6/5} q_5^{2/3} \text{ erg s}^{-1}, \quad (4)$$

其中 $\eta_4 = \eta_{\text{out}}/10^{-4}$ 为能量转换效率. 如此高的能量释放将不可避免地导致外流产生, 而外流与周围气体发生强烈撞击, 会产生激波并形成空腔. 在此过程中积聚的能量最终会爆发, 其能量可与10个超新星爆发所产生的能量相比拟, 该过程称为“Bondi爆炸”. 而空腔在SMBH吸积盘的压力下会被重新填充, 并开始新一轮吸积, 这意味着AMS的吸积过程将是间歇式的.

Bondi爆炸热辐射的典型光变曲线如图4(b)所示,

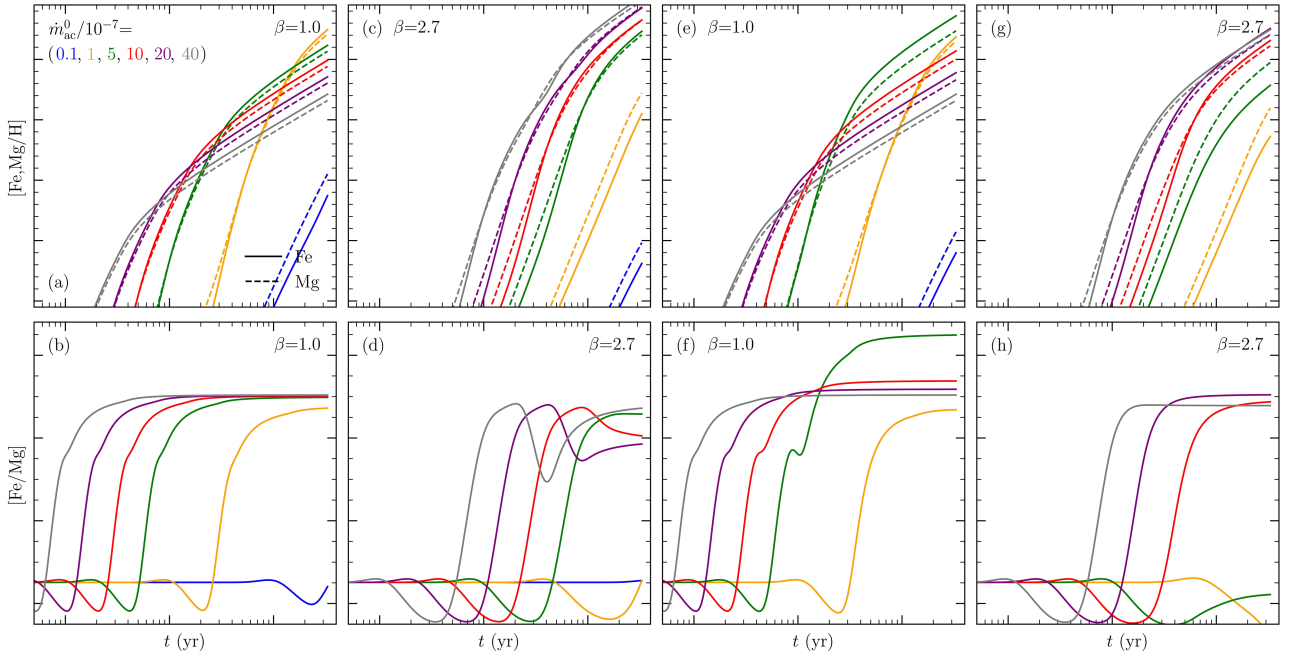


图3 (网络版彩色)AGN盘上铁和镁丰度及[Fe/Mg]丰度比演化过程, 使用恒星模型为超新星爆发能量 $E_{\text{SN}} = 30 \times E_{51}$. (a)~(d)和(e)~(h)分别为无星风与强星风 $\dot{m}_w^0 = 10^{-9} M_{\odot} \text{ yr}^{-1}$ 下的丰度演化过程

Figure 3 (Color online) Evolution of iron and magnesium abundances, and the [Fe/Mg] abundance ratio, on AGN disks, using a stellar model for supernova explosion energy $E_{\text{SN}} = 30 \times E_{51}$. (a)~(d) and (e)~(h) represent the abundance evolution under no stellar wind and high stellar wind conditions with $\dot{m}_w^0 = 10^{-9} M_{\odot} \text{ yr}^{-1}$, respectively

表现为先缓慢爬升后快速高斯式衰减, 光变时标为数月(AMS位于吸积盘中区), 而随着AMS与SMBH距离不同, 该耀发持续时标从几小时(吸积盘内区)到几十年(吸积盘外区)不等. 这为解释与AGN相关的各种天文瞬变事件提供了新的机制. 此外, 由爆炸波加速的相对论电子会产生同步辐射耀斑, 峰值位于软X射线波段(0.1 keV); 电子逆康普顿散射峰值在10 MeV GeV左右, 可被Fermi-LAT探测到; 同时, 对典型的射电宁静类星体的射电、光学、紫外和软X射线波段的辐射也都有重要贡献(图4(a)).

引力波事件GW190521表明AGN盘极可能是致密天体大规模并合的温床. 理论表明, sMBH在吸积盘上迁移的过程中通过雅可比捕获^[65,66]、引力波辐射^[67]、动力学摩擦^[68]以及与周围小盘的碰撞^[69]等过程, 会不可避免地形成双黑洞^[70-73]. 根据AMS的演化过程, 吸积盘上的AMS通常分为两类: I型AMS——sMBH等中心天体周围充满吸积盘气体, 处于高吸积率状态; II型AMS——Bondi爆炸过程中, 外流与周围气体碰撞产生的激波加热周围气体而形成高温且稀薄的空腔,

处于低吸积率状态^[72]. 考虑到Bondi爆炸的占空比极低^[62], 吸积盘上的AMS大多为II型AMS, 因此主要考虑由II型AMS构成的双黑洞的演化过程. 如图5所示, (1) 当两个II型AMS距离足够近时, 在引力作用下会形成双黑洞; (2) 在周围气体压强作用下, 空腔逐渐被填充, 恢复为I型AMS; (3) 在周围气体黏滞作用下, 双黑洞逐渐损失轨道角动量, 距离变小, 随后引力波辐射过程占主导, 导致轨道距离持续减小, 直至发生双黑洞并合事件; (4) 并合后的黑洞产生喷流穿透吸积盘, 并被减速, 形成团状结构; (5) 并合后的黑洞吸积周围气体, 产生强烈外流, 发生Bondi爆炸, 清空周围气体, 变为II型AMS. 以上演化过程可以用来解释GW190521和其潜在电磁对应体之间的时间延迟^[72].

除两个恒星级致密天体的并合外, 由AMS与中心SMBH组成的极端质量比旋进(extreme mass ratio inspiral, EMRI)系统亦可能发生并合而产生引力波^[74,75]. 与通常的“损失锥”形成通道相比, AGN吸积盘可以显著提高EMRI的形成率^[76], 在未来空间引力波探测事例中可能占据相当大比例^[77].

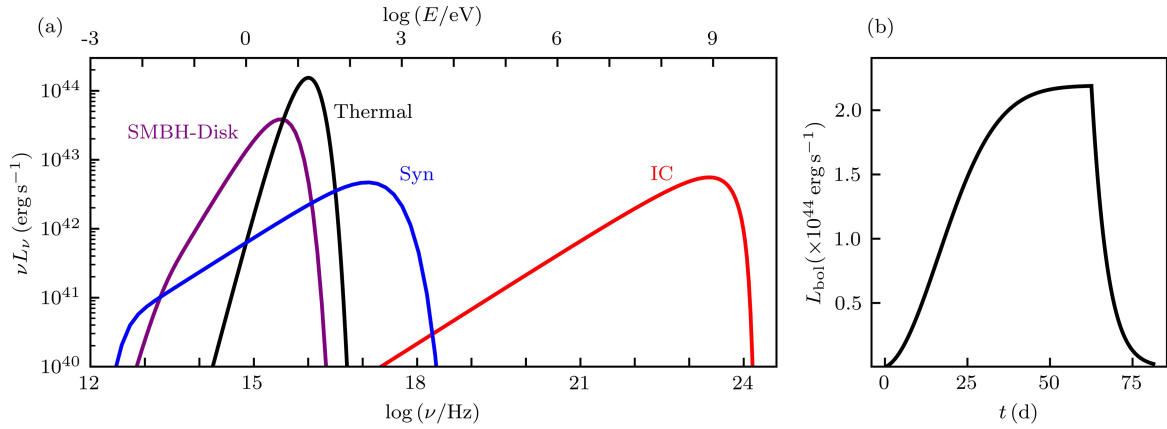


图 4 (网络版彩色)标准盘中AMS的能谱和光变曲线. (a) 被外流激波加热后的SMBH盘气体发出的热辐射, 有效温度为 T_{eff} . 激波加速后的非热电子在磁场中发出同步辐射, 并通过逆康普顿散射过程产生高能光子(GeV能段). (b) 外流热辐射的光变曲线. 缓慢上升的时标为 $t_{\text{rise}} \approx t_{\text{last}}$, 快速衰减的时标为 $t_{\text{decay}} \approx t_{\text{eff}}$

Figure 4 (Color online) SED and light curve of AMS in the accretion disk. (a) The hot gas in the SMBH disk, heated by the outflow shock, emits thermal radiation with an effective temperature of T_{eff} . Non-thermal electrons accelerated by the shock emit synchrotron radiation in the magnetic field and produce high-energy photons (in the GeV energy range) through inverse Compton scattering processes. (b) The light curve of the outflow thermal radiation. The slow-rise timescale is $t_{\text{rise}} \approx t_{\text{last}}$, and the fast-decay timescale is $t_{\text{decay}} \approx t_{\text{eff}}$

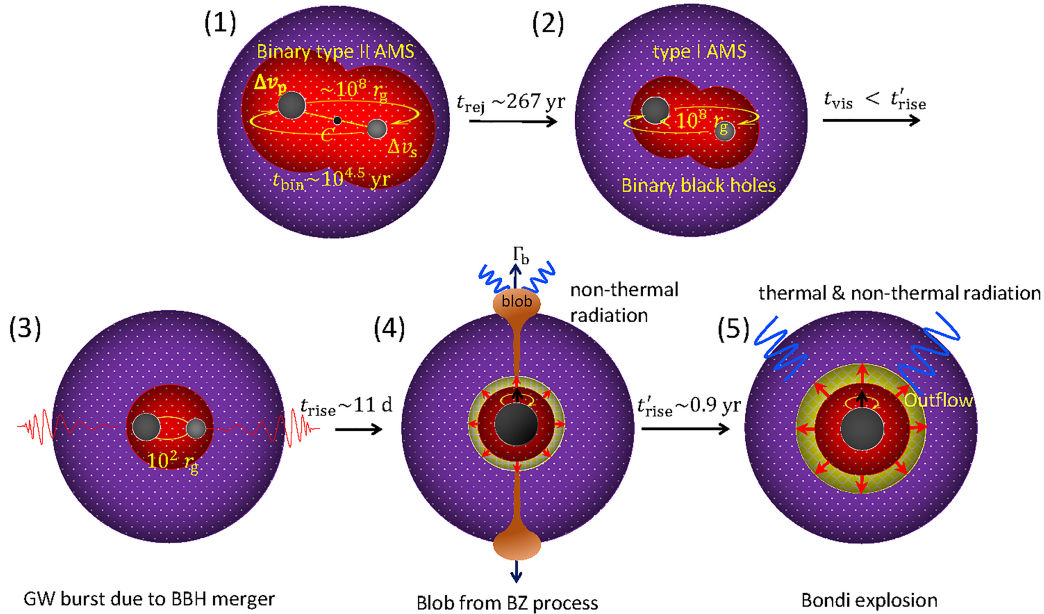


图 5 (网络版彩色)AMS中的双黑洞形成、轨道演化以及并合示意图

Figure 5 (Color online) Illustration of the formation, orbital evolution, and merger of a binary black hole system

3 AMS模型应用:银河系中心

近年来, 随着对银河系中心SMBH($M_{\bullet} = 4 \times 10^6 M_{\odot}$)——人马座A*(Sagittarius A*, Sgr A*)——附近的观测愈发精细, 该区域已成为测试AGN核区恒星形成模型的最佳场所. Bartko等人^[2]通过幂律形式的IMF

拟合银河系中心 $0.8'' \sim 12''$ ($0.03 \sim 0.5$ pc, $10^5 \sim 10^6 R_g$)的恒星盘的K波段光度函数, 发现该盘IMF呈现top-heavy形式, 斜率为 -0.45 . 此外, 甚大望远镜(Very Large Telescope, VLT)的SINFONI IFU在 $30''$ (约1 pc)范围内发现有约200颗年轻恒星分布在翘曲旋转盘上^[3]. 这些恒星可能是Sgr A*曾经活动过程中所形成的恒星的遗留.

因此, Wang等人^[42]将AGN盘中AMS星族演化模型应用于银河系中心的年轻恒星盘. 图6表明, 在AGN一次活动期间, 一组非持续恒星注入的AMS星族演化结果与当前观测到的质量函数非常吻合. 在该模型中, 超新星爆发后将形成80多个黑洞, 这也与根据Chandra探测到的银河系中心pc范围内X射线源的空间分布所推断出的黑洞总数大致吻合^[78]. 此外, 恒星演化过程中超新星的爆发会影响银河系中心的介质. Chandra对银河系中心pc尺度内的观测显示, 若轻元素与太阳丰度类似, 则重元素丰度可达 $1\sim 2Z_{\odot}$, α/Fe 丰度比整体呈现为超太阳的 α/Fe 丰度比^[79], 该模型的计算结果也与上述丰度观测结果相一致. 因此, 这个简单应用表明, AMS星族模型可以解释银河系中心当前的质量函数及其演化过程.

除对Sgr A*附近恒星盘的发现外, 经过几十年数据积累, 人们亦对Sgr A*的能谱分布^[80~83]和多波段的光变特征^[84~88]进行了细致研究. 其中最引人注意的是, 在Sgr A*的近红外与X射线波段都观测到了准周期性闪烁, 而GRAVITY利用四年近红外波段观测数据绘制了多次耀发位置的轨迹, 发现轨迹组成一个环^[89]. 该准周期性闪烁可由等离子体热斑的准周期性结构^[90~93]或热斑的膨胀^[94]解释, 但考虑到SMBH-ADAF(advection dominated accretion flow)内磁重联过程的随机性, 这类模型难以解释耀发总在固定半径处(即 $\sim 9 R_g$)发生. 因此, Leibowitz^[95]曾提出Sgr A*附近存在一颗恒星

作为“起搏器”来解释耀发的准周期性光变. Naoz等人^[96]提出存在一个质量为 $\sim 10^4 M_{\odot}$ 的隐藏黑洞, 不过S2轨道的精确测量结果排除了质量 $\geq 10^3 M_{\odot}$ 的黑洞的存在^[97,98]. 2023年, Wang等人^[74]引入AMS模型—— $40 M_{\odot}$ 的sMBH镶嵌在SMBH的ADAF吸积盘中——解释准周期闪烁及耀发环(图7). 该模型预期在SMBH-ADAF中会准周期性地出现空腔, sMBH吸积成长过程中产生的外流的能量会累积并且将通过黏滞不稳定性产生耀发. 如果sMBH自转很快, 将会通过Blandford-Znajek(BZ)机制形成相对论喷流, 并且产生从射电到伽马波段的以准周期性闪烁的形式出现的非热辐射. 此外, 该模型可以很好地拟合Sgr A*从射电到X波段的能谱, 其中相对论性喷流由周期性的sMBH-ADAF发展而来. 同时, 该EMRI系统将在约30年后发生并合, 并合将产生毫赫兹引力波(应变振幅 $\sim 10^{-17}$). 这是检验银河系中心是否存在AMS的关键, 使得Sgr A*将成为LISA^[99]、太极^[100]、天琴^[101]等引力波探测任务的绝佳目标.

4 总结与展望

本文综述了一个新兴的研究领域, 即活动星系核中心SMBH周围的吸积盘上恒星演化及其观测效应, 它不仅是一个产生各种金属元素的炼金炉, 也是引发各波段引力波事件的天然实验室. 随着引力波时代

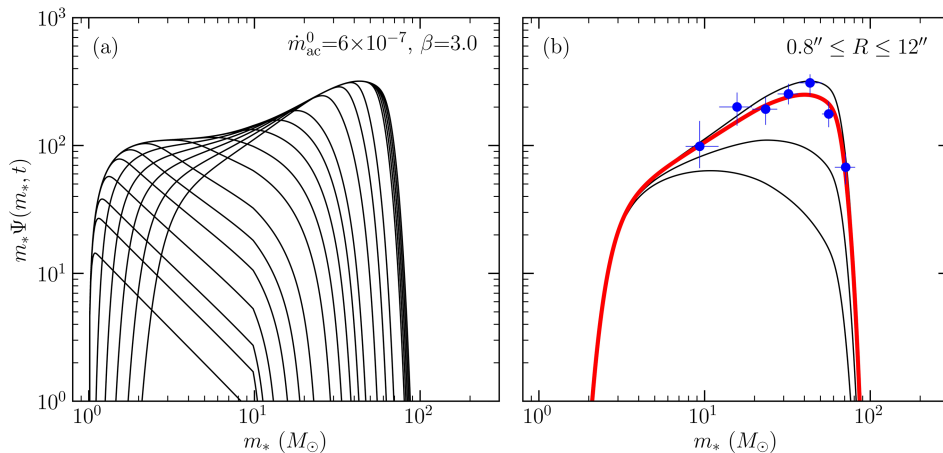


图6 (网络版彩色)对银河系中心年轻恒星盘的应用. (a) 中心SMBH处于活动期间时AMS质量函数的演化, 恒星在 $t_* = 8.5 \times 10^6$ yr时停止注入; (b) SMBH吸积活动停止后AMS的演化, 其中粗线代表质量函数在中心SMBH活动停止 $t \approx 10^6$ yr后的演化状态, 含误差棒的点为观测点^[2]

Figure 6 (Color online) An application to the young stellar disk in the Galactic Center. (a) The MF evolution of AMSs when the central SMBH was active with the star injection stopping at $t_* = 8.5 \times 10^6$ yr. (b) The evolution of AMSs after the SMBH quenches accretion, with the thick solid line depicting an interval of $t \approx 10^6$ yr after the central SMBH stalled, and dots with error bars representing observational data^[2]

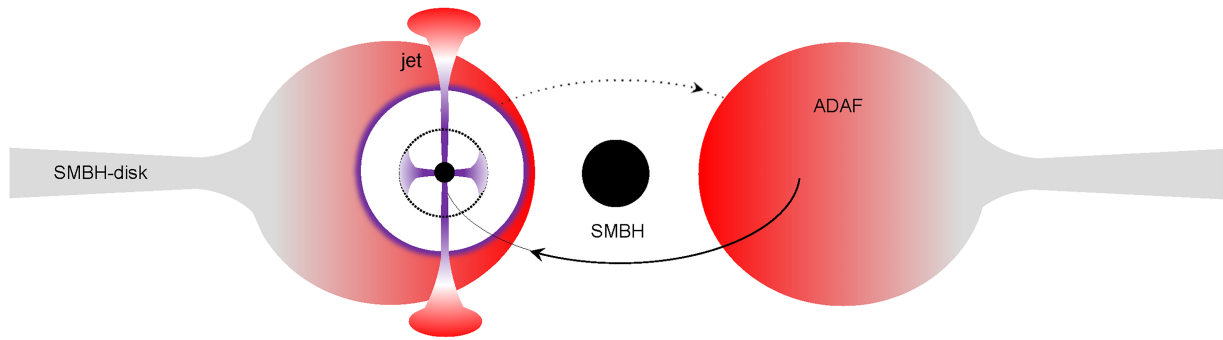


图 7 (网络版彩色) 镶嵌在ADAF吸积盘中的sMBH. sMBH以Bondi吸积率进行吸积, 产生的外流会导致空腔的形成, 并反过来抑制sMBH的吸积. 如果sMBH具有很快的自转, 由于BZ机制会产生相对论性喷流, 喷流产生的电磁辐射则表现为准周期的闪烁. 此外, sMBH外流能量的积累会引发SMBH-ADAF的黏滞不稳定性, 导致在一连串的闪烁之后出现耀发. 该模型可以解释Sgr A* 近红外光变曲线准周期性的闪烁和耀发

Figure 7 (Color online) An sMBH embedded in SMBH-ADAFs. The sMBH is accreting with Bondi rates, forming outflows that lead to the formation of a cavity, suppressing the sMBH's accretion. If sMBH has a rapid rotation, relativistic jets are generated due to the BZ mechanism, and the electromagnetic radiation produced by the jets manifests as quasi-periodic flickering. Furthermore, the accumulation of energy from the sMBH outflows can trigger viscous instability in the SMBH-ADAF, leading to a flare after a series of flickerings. This model can account for the quasi-periodic flickerings and flares observed in the near-infrared light curve of Sgr A*

的开启, 尤其是GW190521引力波并合事件可能发生在AGN盘上, 使得AGN盘上的“微观”物理过程作为新兴研究课题越来越受到人们的关注. 在此背景下, 关于AGN吸积盘中大质量恒星的演化与核合成、致密天体的形成、双星系统的演化(恒星-恒星、致密天体-致密天体、恒星-致密天体)、EMRI系统的演化等问题的研究成为热点. 随着将来更多引力波事件的发现, 上述问题将是未来活动星系核研究的重要课题之一.

在观测上, LIGO/Virgo/KAGRA的引力波探测正在进行中, LISA^[99]、太极^[100]、天琴^[101]等空间低频引力波探测以及Einstein Telescope^[102]、Cosmic Explorer^[103]等第三代地面引力波探测器也正处于建设进程中. 新一代空间及地面引力波探测器有望大幅度提升各种并合事件的探测率, 有助于印证引力波事件与AGN的潜在关联, 为AMS存在于AGN盘中提供独立证据. 其次, GRAVITY+/VLTI观测可以分解核区(pc尺度)的光谱, 这是解开AGN-星暴联系的关键步骤, 将对理解核区的恒星形成与演化有重要贡献. 特别是, GRAVITY/VLTI已经观测到的Sgr A*耀斑位置集中在大约 $9R_g$ 的环上^[89, 104], 显示出存在EMRI的强有力证据. 再者, 密集的时域巡天, 如ZTF^[105]、All-Sky Au-

tomated Survey for Supernovae(ASAS-SN)^[106]与光谱巡天, 如Sloan Digital Sky Survey(SDSS)^[107]、Dark Energy Spectroscopic Instrument(DESI)^[108]将有望在未来继续与引力波探测相协, 实现对引力波事件的多信使联合探测. 这有利于发现更多的电磁对应候选体, 甚至实现对并合时期观测特征的多维度捕捉.

在理论上, AGN盘上的恒星演化与核合成、AGN盘上双星系统以及EMRI系统的演化与并合等问题都处于研究初期. 对于恒星演化而言, 吸积是影响AMS演化的关键要素, 但恒星吸积本身以及AGN盘的环境都会导致AMS吸积变得极为复杂, 具体因素包括: (1) AGN盘的密度和温度及其径向和垂向分布; (2) 包括恒星本身在内的环境的辐射场; (3) AGN盘角动量. 其次, AMS反馈极有可能会影响AGN结构的形成, 如超新星爆发可能支撑膨胀的圆盘作为尘埃环. 对于AGN盘上双AMS或EMRI系统的并合而言, 未来应建立更多模型, 以给出更丰富的、可以直接被数据检验的观测预言, 如多波段光谱特征、光变曲线特征、光变时标特征等, 以便与引力波事件相匹配. 总之, 在引力波时代, 将引力波探测与海量测光、光谱数据相结合, 有望更好地回答AGN盘上各种天体系统的演化问题.

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Summary for “活动星系核: 炼金炉与引力波辐射”

Active galactic nuclei: metallicity and gravitational wave radiation

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In theory, accretion disks around supermassive black holes (SMBHs) exhibit complex structures in the outer regions, where self-gravity inevitably leads to star formation; in observations, particularly from quasar metallicity and recent LIGO gravitational wave detections, there is increasing evidence indicating the presence of massive star formation and evolution in the central regions of active galactic nuclei (AGNs). Due to the dense gas environment in the accretion disks of AGNs, stars and compact objects on these disks have high accretion rates, leading to significant changes in their fate, referred to as “accretion-modified stars” (AMSs). This serves as a focal point for studying the evolution of population evolution, metallicity evolution, and gravitational wave radiation on AGN disks. This has given rise to a novel field with abundant theoretical problems and observational phenomena. The AMSs are allowed to have any metallicity but without significant loss due to stellar winds, since the winds are choked by the dense medium of the disks and return to the core stars. AMS mass functions undergo rapid evolution through accretion, irrespective of the initial mass functions, leading to top-heavy forms characterized by a pile-up or cutoff pile-up shape. Particularly, the cutoff pile-up shape caused by strong stellar winds presents a novel mechanism for generating a narrow window of very massive stars, enabling efficient production of iron through pair-instability supernovae in AGNs. This naturally explains the non-cosmological evolution of [Fe/Mg] of AGNs. Moreover, supernova explosions of AMSs support an inflated disk as a dusty torus. On the other hand, AMSs can generate stellar-mass black holes through supernova explosions, forming a population of satellite black holes around SMBHs. Stellar-mass black holes on accretion disks typically exhibit extremely high accretion rates. The intense gravitational energy release process can result in strong outflows, interacting with the surrounding gas and leading to a Bondi explosion. The nonthermal radiation of Bondi explosions peaks in the X-ray and gamma-ray bands, with the luminosity of the thermal radiation reaching up to $\sim 10^{44} \text{ erg s}^{-1}$. If black holes on accretion disks are close enough during their migration process, they may form binary black holes. The interaction with the surrounding gas could accelerate the merger process, providing a potential explanation for mergers of massive black holes. Furthermore, the AMS model can provide a reasonable explanation for the top-heavy stellar disk and metallicity in the Galactic center, where a satellite black hole with $40 M_{\odot}$ can account for phenomena such as infrared flickering period and flaring orbit. It may represent the closest EMRI (extreme mass ratio inspiral) object to Earth. In the future, the combination of more gravitational wave detections with spectroscopic and photometric observation programs holds the promise of better addressing the evolution and merger issues of stars and compact objects on AGN disks.

active galactic nuclei, supermassive black holes, accretion disks, gravitational waves

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