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X射线双星的形成与演化

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X射线双星是包含一颗吸积致密星(黑洞、中子星或者白矮星)的双星系统, 是宇宙中的重要天体. 对它们的研究不仅可以帮助人们理解双星演化、吸积盘和致密星物理, 而且也有助于对星系的形成和演化历史甚至宇宙学模型的认识. 本文的目的是讨论X射线双星的形成和演化过程, 涉及到Be/X射线双星、低质量X射线双星、极亮X射线源和激变变星. 第1章我们简要介绍了双星演化的相关知识.

第2章我们讨论通过双星相互作用渠道来形成Be星. 我们研究双星中的物质转移对恒星自转的影响. 通过双星演化和星族合成计算, 我们发现: 如果经历了稳定的(没有公共包层演化发生)和非守恒的质量转移, Be/中子星双星中的Be星质量下限可以达到$\sim 8\ M_\odot$. 我们的工作还表明: 孤立的Be星可能起源于2个主序星的并合和超新星爆炸破坏的Be双星, 但合并过程扮演了更重要的角色. 最后, 通过双星相互作用产生的Be星在所有B型星中所占的百分比可以高达$\sim$ 13%–30%, 意味着大多数的Be星是通过双星相互作用产生的.

第3章介绍了中等质量和低质量X射线双星与毫秒脉冲星的演化联系. 通过数值计算, 并与观测结果比较, 我们得到如下结论: (1)在初始的轨道周期-伴星质量平面上, 形成双星脉冲星所允许的参数空间随着中子星质量的增加而增大. 这也许能够帮助解释为什么一些轨道周期长于$\sim$ 60 d的系统中, 毫秒脉冲星的白矮星伴星质量似乎比期望值更小. 另一种可能性是, 一些宽轨道的双星脉冲星可能是通过行星/褐矮星参与的公共包层演化的渠道形成的; (2)一些密近的双星脉冲星可能是由中等质量X射线双星演化而来的, 但要求伴星具有异常高的磁场; (3)在低质量X射线双星中, 中子星的平衡自旋周期比观测到的双星脉冲星的自旋周期短一个量级以上, 表明: 要么简单的平衡自旋模型有缺陷, 要么存在其他的自旋减速机制.

第4章我们分析了周期空隙下方的激变变星的角动量损失机制. 通过考虑几种可能的角动量损失机制, 我们发现: 白矮星吸积产生的各向同性星风和L_1点的外流都不能解释这个额外的角动量损失率, 而L_2点的外流可以有效地提取角动量, 这里要求物质转移时有$\sim$ 15%–45%的物质逃逸出双星系统. 更有效的机制是由CB (Circumbinary)盘施加的引力力矩来提取角动量. 在这种情况下, 质量损失比例可以低至$\lesssim 10^{-3}$.

我们在第5章对由吸积中子星形成的极亮X射线源进行了研究. 大多数的极亮X射线源都被认为是X射线双星系统, 但是以前的观测和理论研究都趋向于认为有一个黑洞(而不是中子星)在吸积. 对极亮X射线源M82 X-2, 最近发现的1.37 s的脉冲表明吸积星是一个磁中子星. 我们模拟了M82和类银河系中的中子星极亮X射线源的形成历史, 结合双星星族合成和详细的双星演化计算, 我们发现两种情形下的初始的X射线双星的诞生率在$10^{-4}\,\mathrm{yr}^{-1}$左右. 我们给出了极亮X射线源在伴星质量-轨道周期平面上的分布. 与黑洞X射线双星相比较, 中子星X射线双星对极亮X射线源星族的贡献相当甚至可能更多, 高质量/中等质量X射线双星分别主导着M82/类银河系中的中子星极亮X射线源.

第6章中, 我们讨论了银河系内中等质量和低质量X射线双星的形成和演化. 通过星族合成和恒星

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演化计算, 我们得到了银河系内中等质量和低质量X射线双星的诞生率、它们的演化轨迹和分布特征. 然后我们追踪X射线双星的演化, 直到形成双星毫秒脉冲星. 计算结果表明: 演化中的X射线双星更有可能以密近系统的形式被观测到, 双星毫秒脉冲星的轨道周期处在$\sim$ 1天到几百天范围内. 这些特征与观测到的低质量X射线双星和双星毫秒脉冲星相符. 我们证实了以前文献中提到的理论预期和观测之间的偏离. 也就是, 理论上X射线双星中的平均物质转移率比观测值低很多, 轨道周期处在0.1–1 d的双星毫秒脉冲星数目是严重低估的. 这些都表明: 模拟低质量X射线双星演化时, 某些因素未被考虑, 很有可能与轨道角动量损失机制相关.

最后, 我们在第7章总结全文, 并对以后的工作作出展望.

Formation and Evolution of X-ray Binaries

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X-ray binaries are a class of binary systems, in which the accretor is a compact star (i.e., black hole, neutron star, or white dwarf). They are one of the most important objects in the universe, which can be used to study not only binary evolution but also accretion disks and compact stars. Statistical investigations of these binaries help to understand the formation and evolution of galaxies, and sometimes provide useful constraints on the cosmological models. The goal of this thesis is to investigate the formation and evolution processes of X-ray binaries including Be/X-ray binaries, low-mass X-ray binaries (LMXBs), ultraluminous X-ray sources (ULXs), and cataclysmic variables. In Chapter 1 we give a brief review on the basic knowledge of the binary evolution.

In Chapter 2 we discuss the formation of Be stars through binary interaction. In this chapter we investigate the formation of Be stars resulting from mass transfer in binaries in the Galaxy. Using binary evolution and population synthesis calculations, we find that in Be/neutron star binaries the Be stars have a lower limit of mass $\sim 8\ M_{\odot}$ if they are formed by a stable (i.e., without the occurrence of common envelope evolution) and nonconservative mass transfer. We demonstrate that the isolated Be stars may originate from both mergers of two main-sequence stars and disrupted Be binaries during the supernova explosions of the primary stars, but mergers seem to play a much more important role. Finally the fraction of Be stars produced by binary interactions in all B type stars can be as high as $\sim 13\%$–30%, implying that most of Be stars may result from binary interaction.

In Chapter 3 we show the evolution of intermediate- and low-mass X-ray binaries (I/LMXBs) and the formation of millisecond pulsars. Comparing the calculated results with the observations of binary radio pulsars, we report the following results: (1) The allowed parameter space for forming binary pulsars in the initial orbital period-donor mass plane increases with the increasing neutron star mass. This may help to explain why some millisecond pulsars with orbital periods longer than ~ 60 d seem to have less massive white dwarfs than expected. Alternatively, some of these wide binary pulsars may be formed through mass transfer driven by planet/brown dwarf-involved common envelope evolution; (2) Some of the pulsars in compact binaries might have evolved from intermediate-mass X-ray binaries with an anomalous magnetic braking; (3) The equilibrium spin periods of neutron stars in low-mass X-ray binaries are in general shorter than the observed spin peri-

ods of binary pulsars by more than one order of magnitude, suggesting that either the simple equilibrium spin model does not apply, or there are other mechanisms/processes spinning down the neutron stars.

In Chapter 4, angular momentum loss mechanisms in the cataclysmic variables below the period gap are presented. By considering several kinds of consequential angular momentum loss mechanisms, we find that neither isotropic wind from the white dwarf nor outflow from the L_1 point can explain the extra angular momentum loss rate, while an ouflow from the L_2 point or a circumbinary disk can effectively extract the angular momentum provided that $\sim$ 15%–45% of the transferred mass is lost from the binary. A more promising mechanism is a circumbinary disk exerting a gravitational torque on the binary. In this case the mass loss fraction can be as low as $\lesssim 10^{-3}$.

In Chapter 5 we present a study on the population of ultraluminous X-ray sources with an accreting neutron star. Most ULXs are believed to be X-ray binary systems, but previous observational and theoretical studies tend to prefer a black hole rather than a neutron star accretor. The recent discovery of 1.37 s pulsations from the ULX M82 X-2 has established its nature as a magnetized neutron star. In this chapter we model the formation history of neutron star ULXs in an M82- or Milky Way-like galaxy, by use of both binary population synthesis and detailed binary evolution calculations. We find that the birthrate is around 10^{-4} yr^{-1} for the incipient X-ray binaries in both cases. We demonstrate the distribution of the ULX population in the donor mass - orbital period plane. Our results suggest that, compared with black hole X-ray binaries, neutron star X-ray binaries may significantly contribute to the ULX population, and high/intermediate-mass X-ray binaries dominate the neutron star ULX population in M82/Milky Way-like galaxies, respectively.

In Chapter 6, the population of intermediate- and low-mass X-ray binaries in the Galaxy is explored. We investigate the formation and evolutionary sequences of Galactic intermediate- and low-mass X-ray binaries by combining binary population synthesis (BPS) and detailed stellar evolutionary calculations. Using an updated BPS code we compute the evolution of massive binaries that leads to the formation of incipient I/LMXBs, and present their distribution in the initial donor mass vs. initial orbital period diagram. We then follow the evolution of I/LMXBs until the formation of binary millisecond pulsars (BMSPs). We show that during the evolution of I/LMXBs they are likely to be observed as relatively compact binaries. The resultant BMSPs have orbital periods ranging from about 1 day to a few hundred days. These features are consistent with observations of LMXBs and BMSPs. We also confirm the discrepancies between theoretical predictions and observations mentioned in the literature, that is, the theoretical average mass transfer rates of LMXBs are considerably lower than observed, and the number of BMSPs with orbital periods $\sim$ 0.1–1 d is severely underestimated. Both imply that something is missing in the modeling of LMXBs, which is likely to be related to the mechanisms of the orbital angular momentum loss.

Finally in Chapter 7 we summarize our results and give the prospects for the future work.