Accreting black holes

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1.1 Formation of Black Holes

Black holes are one of the most exotic and fascinating objects in the Universe. A black hole is mathematically defined to be a single point-like region, the so called singularity, where gravity is so strong that anything close enough to it will eventually be dragged across its event horizon (the point of no return) and forever vanish from our view; even light can not escape from such a strong gravitational pull.

Black holes can weigh from a few solar masses (stellar-mass black holes) to billions of solar masses (supermassive black holes). Stellar-mass black holes are normally found in the Galactic disk and bulge, and recently there has been evidence indicating that they also exist in globular clusters (Maccarone et al. 2007, 2011; Strader et al. 2012). We now have a very good understanding about how a stellar-mass black hole forms. Typically, they form when massive stars directly collapse at the end of their life cycle. Unlike stellar-mass black holes, super-massive black holes are found in the center of galaxies. The best example is Sgr. A* in the center of our Milky Way Galaxy. These supermassive black holes can weigh from $10^6$ to even $10^{11} M_\odot$ (Sgr. A* is roughly 4 million solar masses). There is not yet a definite conclusion on how supermassive black holes actually form. The most widely accepted explanation is that they are formed from mergers of seed black holes (Volonteri & Rees 2005). These seed black holes are suggested to weigh from $10^2$ to $10^5 M_\odot$, which are in the range of the intermediate masses. However, the formation process and the initial weight of these seed black holes are still a matter of debate. Some think that they are formed by the direct collapse of Population III stars (in a similar process as the formation of stellar-mass black holes, but with heavier progenitor stars). Theo-
retically, population III stars can be produced in the early Universe (Abel, Bryan & Norman 2000; Bromm, Coppi & Larson 2002), and they have much higher initial masses. Since the progenitor is much heavier, the remaining black hole mass after a star collapses is also expected to be large. In addition, some theories have also proposed that these seed black holes can be formed from the collapse of primordial gas disks or proto-galaxies (Lodato & Natarajan 2006, 2007). Currently, we are not able to determine which scenario is more likely. Future missions (such as the James Webb Space Telescope) with better detecting capability can make much deeper observations to probe the early Universe, which may answer these questions.

Black holes can continue to grow by accreting matter from their surrounding gas and materials. This accretion process emits radiation in different energies depending on the mass of the central black hole. For example, the radiation from an accreting stellar-mass black hole is normally in X-rays, and is in optical for a supermassive black hole. This is also how we can observe activity from black holes and indirectly demonstrate their existence.

1.2 Mass Measurements of Black Holes

Typically, for a stellar mass black hole, we can obtain very accurate mass by measuring its orbital relation with the optical companion (e.g. Figure 1.1 shows black holes with confirmed dynamical mass measurements). However, this only works when the source is relatively close to us and has a bright companion star. For sources at large distances or in external galaxies, the companion star would be too dim to be observed. In the case of a supermassive black hole in the center of a galaxy, we can study dynamics of the stars orbiting around the central black hole and estimate the black hole mass. For example, the mass of Sgr. A* (4 × 10⁶ M⊙) at the center of our Milky Way galaxy was accurately measured through monitoring the motion of nearby stars. The drawback is that it takes a long time to trace the motions of these stars, and for nuclear black holes in distant galaxies, it is impossible to observe each individual nearby star because of limits in the instruments. However, we can still study the average gas motions near the galactic center as the faster the motion is, the stronger gravity affects the surrounding gas motion, indicating the presence of a black hole with large mass. On the other hand, as the central black hole mass decreases, the star motions become much more difficult to detect. They become too dim to be observed and the star light might also be obscured by dust in the interstellar medium.

The best way to study low-mass black holes is probably when they are accreting matter from the surrounding environment and form an accretion disk. An alternative
1.2 Mass Measurements of Black Holes

Figure 1.1: Schematic diagram of 20 dynamically confirmed black hole X-ray binaries (courtesy of Jerome Orosz; http://mintaka.sdsu.edu/faculty/orosz/web/). 17 of them are LMXBs, and 3 of them (Cyg X-1, LMC X-1 and LMC X-3) are HMXBs.

...method for estimating black hole masses that can be applied under such conditions is the so called 'fundamental plane'. The 'fundamental plane' is an empirical relationship correlated between the X-ray luminosity (normally thought to be from the accretion disk), radio luminosity (from the jet emission) and the black hole mass for accreting black holes in the low/hard state (Merloni et al. 2003; Falcke et al. 2004; Körding et al. 2006). The relationship can be extended from stellar-mass black holes (X-ray binaries) all the way to supermassive black holes (AGNs).

There have been several studies utilizing this method to obtain the approximate masses of black holes in cases where all other methods could not work. For example, it has been found that the intermediate mass black hole (IMBH) HLX-1 has state transitions that are similar to stellar-mass black holes (Webb et al. 2012). A jet
emission (in radio) was also detected during the low/hard state transition that is in common with many Galactic black hole binaries (this indicates that this type of state transitions and disk-jet coupling might be common and can be expected not only from the stellar-mass and supermassive black holes, but also from black holes with masses in between). This provides us necessary information to obtain the black hole mass using the ‘fundamental plane’. It was found that the black hole in HLX-1 has a mass of \( \sim 500M_\odot \). Another example is an active galactic nucleus (AGN) in Henize 2-10 (Reines et al., 2011). The mass of the AGN reported was also calculated using the fundamental plane.

### 1.3 X-ray Binaries

Since black holes do not emit light, in order to study them, we can observe them when they are interacting with their surrounding materials. For stellar-mass black holes, we study them when they are in binary systems. Since these systems emit in X-rays when they are active, we call them X-ray binaries. X-ray binaries with a black hole accretor can also be divided into two subgroups: the high-mass X-ray binaries (HMXBs) and the low-mass X-ray binaries (LMXBs).
1.3 X-ray Binaries

1.3.1 HMXBs

An HMXB is a binary star system that has a donor star > 10\(M_\odot\) (i.e. blue O or B class giant or Be star), and a compact primary (can be a neutron star, black hole or a white dwarf). The donor star feeds the compact primary through its stellar wind. A fraction of the stellar wind from the donor is captured by the compact primary and forms an accretion disk around it. In HMXBs, the massive donor star mainly radiates in optical bands, while the compact object radiates in X-rays. Figure 1.2 shows an artist’s impression of the most well-known black hole HMXB Cyg X-1.

1.3.2 LMXBs

An LMXB is a binary system where the primary component is a compact object (either a black hole or a neutron star). The secondary donor star is normally less massive than the primary. It can be a main sequence star, a degenerate dwarf (i.e. white dwarf), or an evolved star (red giant). The donor transfers mass to the compact star via Roche-lobe overflow. LMXBs normally emit very strong X-rays when they are in outburst. We can therefore study their accreting process and physical properties through X-ray observations. Figure 1.3 shows an artist’s impression of the structure of an LMXB.
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Figure 1.4: Left panel shows the X-ray energy spectra of the black hole in different states. Right panel shows the disk structure and the distribution of matter flowing around the black hole in different states (Done, Gierliński & Kubota 2007).

1.4 Soft X-ray Transients

A fraction of the low mass X-ray binaries were identified by their transient behavior, timing and spectral properties (normally in soft X-ray bands), and therefore also denoted as soft X-ray transients (SXTs; Tanaka & Lewin 1995; van Paradijs & McClintock 1995). SXTs spend most of their lifetime in the quiescent state, and occasionally undergo dramatic outbursts which could last from weeks to even years for some extreme cases. The typical maximal luminosity of an X-ray outburst for such systems ranges from $10^{36}$ to $10^{38}$ erg s$^{-1}$, and the lower bound can go as low as $10^{30}$ erg s$^{-1}$.

1.4.1 Accretion States

It has long been recognized that Galactic black hole binaries demonstrate various X-ray spectral states which are defined by a balance between the power-law and the disk blackbody components. The three most familiar X-ray bright states are the low/hard (LH), high/soft (HS, also described as ‘thermal dominated’) and the very high (VH, or ’steep power law’) states (McClintock & Remillard 2003, 2006). The LH state is usually characterized by a strong power-law component (>~80 percent with power-law photon index $\Gamma$ ~1.7) with low source luminosity, and is sometimes associated with
1.4 Soft X-ray Transients

Figure 1.5: A schematic representation for black hole state transitions and disk-jet coupling (from Fender et al. 2004). The X-ray states are labeled as HS=high/soft state, VHS/IS=very high and intermediate states, and LS=low/hard state.

the presence of a quasi-steady radio jet. The HS state is usually characterized by a strong thermal component of the radiation from the inner accretion disk (>75 percent of the total flux). There is sometimes a second non-thermal component present in the spectrum, but the overall contribution is very small. The VH or steep power law state (SPL) is somewhat similar to the HS state, but with a strong power-law contribution (~50 percent) and relatively soft power-law photon index ($\Gamma > 2.4$). The VH/SPL state tends to dominate the spectra as the X-ray luminosity reaches the Eddington limit. Figure 1.4 shows how the X-ray energy spectra appear and the distribution of the matter and structure of the disk around the black hole in the different states. Figure 1.5 shows the hardness intensity diagram (the so-called q diagram) of a black hole system that transits between different states and its relation with the radio jet.

1.4.2 Outbursts

We now have a very good understanding of how a black hole behaves when it transitions into an outburst, especially at the beginning of the outburst and when it is in the bright luminosity phase. However, the accretion process is poorly understood in
Figure 1.6: X-ray lightcurve of the black hole X-ray binary MAXI J1659-152.

Figure 1.7: X-ray lightcurve of the black hole X-ray binary MAXI J1836-194.
1.5 Ultra-luminous X-ray Sources

Ultra-luminous X-ray sources (ULXs) are defined as off-nuclear X-ray sources with isotropic luminosities much higher than the Eddington limit for a stellar-mass black hole \((L_X \sim 1.3 \times 10^{38} \text{ erg s}^{-1})\). Typical X-ray luminosities of ULXs are between \(10^{39} \text{ erg s}^{-1}\) and a few \(\times 10^{41} \text{ erg s}^{-1}\). The physical nature of ULXs has been an enigma because of their high energy output. Many ULXs show strong variability suggesting that they are accreting compact objects. Assuming the emission is isotropic, then some of the ULXs may harbor intermediate-mass black holes (IMBHs; Colbert & Mushotzky 1999; Makishima et al. 2000) with masses of \(10^0 - 10^5 \text{M}_\odot\). Alternatively, ULXs may simply be stellar-mass black holes either accreting at super-Eddington rates or exhibiting some degree of geometric or relativistic beaming. It has been suggested that ULXs are stellar-mass black holes with radiation pressure-dominated (Begelman 2002) or slim (Ebisawa et al. 2003) accretion disks that cause super-Eddington luminosities. Furthermore, ULXs may be stellar-mass black holes with anisotropic X-ray emission (King et al. 2001), or microblazars which happened to be observed along the direction of their relativistically beamed jet (Körding et al. 2002). In addition, some ULXs may be young X-ray luminous supernova remnants in a high-density medium, or hypernova remnants. Each of these models have difficulties in fully explaining the observations of these sources, but still have some supporting evidence. Currently, we do not have a complete picture of the physical nature of ULXs, primarily because we do not have dynamical mass measurements of the compact objects that power ULXs.

Recently, there have been simulations that showed that it is possible to produce black holes with much more mass than typical stellar mass black holes (> 30 solar mass, Mapelli et al. 2010) in low-metallicity environments. If true, with black holes having such masses, we can easily explain the ULXs with X-ray luminosities...
above $10^{40}$ to $10^{41}$ erg s$^{-1}$, though not for sources with X-ray luminosities $\sim 10^{42}$ erg s$^{-1}$. This will require very extreme physical conditions, or an IMBH. It has been a long debate whether or not IMBHs exist. Very recently, we finally have a firm case (HLX-1, Farrell et al. 2009). This is the strongest and most thoroughly studied IMBH case to date. Although we still need more source detections to firmly establish its type, the idea of IMBHs has been gradually accepted in the astronomy community.

It is widely accepted that most ULXs are associated with young and dense star clusters (i.e. the star-forming regions, Swartz et al. 2004, 2008; Gilfanov et al. 2004; Liu et al. 2006), where the stellar density is so high that we can naturally expect the birth of massive stars, and violent emission activities. Several studies on the connection between ULXs and the environment of their host galaxies have been carried out. It has been found that most ULXs we discovered up to now are in starburst galaxies, metal-poor dwarf galaxies, merging and tidally interacting galaxies. These systems usually contain dense and young star clusters which provide an ideal environment for producing heavy objects.

Optical counterparts of some ULXs have been identified, and are typically found to be consistent with high mass stars (e.g. O stars), sometimes showing evidence for variability and blue spectra possibly indicative of an accretion disk (e.g. Ramsey et al. 2006; Roberts et al. 2008; Kaaret & Corbel 2009). In addition, a large fraction of ULXs appear to be associated with extended nebulae; supershells that are
hundreds of parsecs in diameter (e.g. Pakull & Mirioni 2002; Ramsey et al. 2006; Abolmasov et al. 2007; Kaaret & Corbel 2009). From time-resolved studies of the optical counterparts, it is possible to obtain dynamical mass constraints, which may confirm the existence of intermediate-mass black holes (IMBHs) in some ULXs (for $L_X > 10^{40}$ erg s$^{-1}$). In addition, the large supershells are found to be powered by photoionization and/or shock-excitation from the ULX. This places constraints on the isotropic or beamed nature of the X-ray emission; since forbidden line regions will radiate isotropically, photoionization from forbidden lines cannot be increased by geometric beaming. Figure 1.8 shows two ULXs (Yang et al. in prep.), a possible IMBH (chapter 8) and its optical counterpart in the metal-poor blue compact dwarf galaxy NGC 4861.

1.6 Summary: Thesis Outline

In addition to the introduction (chapter 1), this thesis contains 7 scientific chapters with topics ranging from stellar-mass to intermediate mass black holes, from their quiescent to super-Eddington states. Chapters 2, 3 and 4 are about stellar-mass black holes in their quiescent states. Chapter 5 is about a stellar-mass black hole (or an unusual neutron star) accreting near or at super-Eddington rate. Chapters 6 and 7 are about ULXs and their optical associations. Chapter 8 is about the detection of a possible IMBH in the center of a blue compact dwarf galaxy. Finally, the thesis ends with a summary.

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