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Black Hole Mass of Microquasars and Quasars

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Abstract The methods that were adopted to estimate the black hole mass in black hole X-ray binaries and active galactic nuclei are briefly reviewed. The relations of black hole masses with other properties, such as X-ray variability, QPOs, radio and X-ray luminosities, are discussed and the analogy of microquasars and quasars is further demonstrated.

Key words: accretion, accretion disks — black hole physics — galaxies: active — X-rays: binaries

1 INTRODUCTION

The analogy between microquasars, Galactic black hole X-ray binaries having superluminal jets, and quasars has been well demonstrated in the last decade (Mirabel & Rodríguez, 1994, 1999; Mirabel 2001). Although with different distances and different black hole masses, microquasars and quasars have many similarities with each other. They are similar not only in the morphology but also in the underline physics. Current understandings of the physics of microquasars and quasars all depend on our knowledge on the central black hole, accretion disk, relativistic jet, bright radio lobe, etc.

In comparison with the study on quasars (or active galactic nuclei (AGN) in general), there are a lot of advantages in studying microquasars. First, many microquasars are in our Galaxy so they are near to us. The observations on them are relatively easier than most quasars. Second, variability time scales of black hole systems are probably proportional to the mass of the black hole. Since microquasars usually have black hole masses of about 10 solar masses, they have much shorter variability time scales than quasars. So we can observe many circles of their light variations within a relatively short time, which is, however, very difficult for quasars whose variability time scales are usually of years. Therefore, the close study on Galactic microquasars is very much helpful to understand the nature of quasars since the physics of accretion flow and jet formation process are probably the same in these two kinds of objects.

In this paper we will focus on the estimations of black hole masses for microquasars and quasars and the relations of black hole masses with other observed properties in these systems.

2 BLACK HOLE MASS OF MICROQUASARS

Since microquasar is a black hole X-ray binary, the estimation of its black hole mass can be done with measuring the orbit period and the radial velocity of the companion star. According

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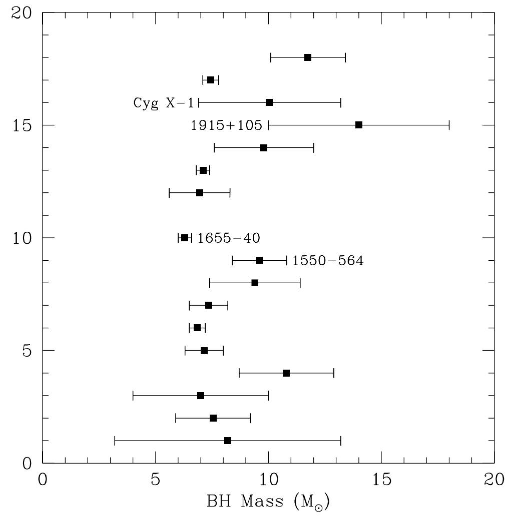

Fig. 1 Black hole mass distributions of 17 black hole X-ray binaries. The data are from Table 4.2 in McClintock & Remillard (2003).

to the Kepler's third law, we have

$$\frac{G(M_p+M_s)}{a^3}=(\frac{2\pi}{P})^2, \tag{1}$$

where M_p and M_s are the masses of compact star and companion star respectively, a is the separation between two stars and P is the orbit period. From this equation we can derive the mass function as:

$$f(M)=\frac{M_p\sin^2 i}{(1+M_s/M_p)^2}=\frac{PK_s}{2\pi G}, \tag{2}$$

where K_s is the radial velocity of the companion star and i is the inclination angle between the normal of orbit plane and the line of sight. Therefore from the observations we can determine the mass function. The black hole mass can be then derived by

$$M_p=\frac{f(M)(1+M_s/M_p)^2}{\sin^3 i}, \tag{3}$$

if the mass of the companion star and the inclination are known. For microquasars with clearly detected jets, the inclination of the orbit plane can be derived from their jet velocity.

So far the black hole masses of 17 black hole X-ray binaries, including those of several well-known microquasars, have been measured using the method described above. The results were summarized in Table 4.2 of McClintock & Remillard (2003). In Fig. 1 we show the distribution of the black hole masses of these sources. The range of black hole mass distribution is from 3 to 18 $M_\odot$, with an average of about 9 $M_\odot$.

The determinations of black hole masses in microquasars are important for understanding many observed phenomena. For example, a possible anti-correlation between the high-frequency(>100 Hz) QPO frequencies and black hole masses, namely, ν_0 = 93.1 Hz $(M/10M_\odot)^{-1}$, has been found for 3 microquasars (McClintock & Ramillard 2003). This may be consistent with the expression of Keplerian frequency, which is: ν_ϕ =

$102\,\mathrm{Hz}(R/10R_g)^{-1/2}(M/10M_\odot)^{-1}$. Because the high-frequency QPOs probably come from an area near the innermost stable circular orbit, using the Keplerian frequency at this radius we can also estimate the black hole spin. In addition, the black hole mass data can be used to calculate the Eddington ratio at the quiescent state, namely $L_{\min}/L_{\mathrm{Edd}}$, which is helpful to distinguish the physics nature between neutron stars and black holes (McClintock et al. 2003). Since black hole has no hard surface, the Eddington ratio of a black hole X-ray binary at the quiescent state should be lower than that of neutron star X-ray binary. This has been indeed shown by the data collected with the space X-ray telescopes.

3 BLACK HOLE MASS OF AGN

In order to explain the huge energy output of quasars, Lynden-bell (1969) suggested that a supermassive (more than 1 million solar masses) black hole may exist in quasars. However, to prove the existence of supermassive black holes in the universe is not easy. Thanks to the Hubble Space Telescope and other huge ground-based telescopes, the black hole masses of about 40 nearby galaxies have been measured in last decade using the methods of stellar, gas and watermaser dynamics (see Kormendy & Gebhardt 2001 for a review). Because most AGNs are usually bright in the nuclear, the dynamics method can not directly apply to them. We have to seek for other ways to estimate the black hole masses for AGNs.

One successful way is to use the reverberation mapping technique, which is applicable to broad line AGNs (Peterson 1997). By doing a long-term monitoring of both continuum and broad emission lines, we can measure the delay between the variations of emission line flux and continuum flux. Because such a delay corresponds to the light travel time between the continuum source and the line-emitting gas, the broad line region(BLR) size can be obtained from the delay time, $R_{\mathrm{BLR}} = c\Delta t$. Moreover, the gas velocity in the BLR can be estimated from the width of emission line (H_β for example) by $V = f \times \mathrm{FWHM}(\mathrm{H}_\beta)$, where $f = \sqrt{3}/2$ for a random distribution of the BLR inclination. Therefore the black hole mass of AGN can be obtained from the virial theorem:

$$M_{\mathrm{BH}} = \eta \frac{V^2 R_{\mathrm{BLR}}}{G}, \qquad (4)$$

where η describes various uncertainties of the method and is usually of order of unity. With the reverberation mapping technique, the black hole masses of 37 nearby quasars and Seyfert galaxies have been estimated (Wandel, Peterson & Malkan 1999; Ho 1999; Kaspi et al. 2000). All these black hole masses are in a range from 10^6 to $10^9\,M_\odot$.

Using the observed data of 34 nearby AGNs in the reverberation mapping studies, an empirical relation between the BLR size and the optical/UV continuum luminosity has been derived by Kaspi et al. (2000) and Vestergaard (2002). This R-L relation provides a possibility to estimate the BLR size and then the black hole mass of an AGN by measuring the continuum flux and broad emission line width from a single optical/UV spectrum. Therefore, it has been frequently adopted to derive the black hole masses for a number of AGNs, including the most distant quasar at $z = 6.4$ (Willott et al. 2003; Barth et al. 2003). However, the optical/UV luminosity of some radio-loud AGNs may not be a good indicator of ionizing luminosity, which is usually related to the radiation from the accretion disk around the central black hole. The powerful jets of blazar-type AGNs may significantly contribute to the optical luminosity. Therefore, using the previous empirical $R-L$ relation, which was obtained based on the sample of mostly radio-quiet AGNs, one would significantly overestimate the actual BLR size and hence the black hole mass of radio-loud AGNs. Using the available data of BLR sizes and H_β fluxes for 34 AGNs in the reverberation mapping studies, we derive an empirical relation between the BLR size and H_β luminosity. With an ordinary least square (OLS) bisector method we obtained (Wu et al. 2004):

$$\log\ R\ (\mathrm{light-days}) = (1.381 \pm 0.080) + (0.684 \pm 0.106) \log\ (\mathrm{L}_{\mathrm{H}_\beta}/10^{42}\ \mathrm{erg\ s^{-1}}). \qquad (5)$$

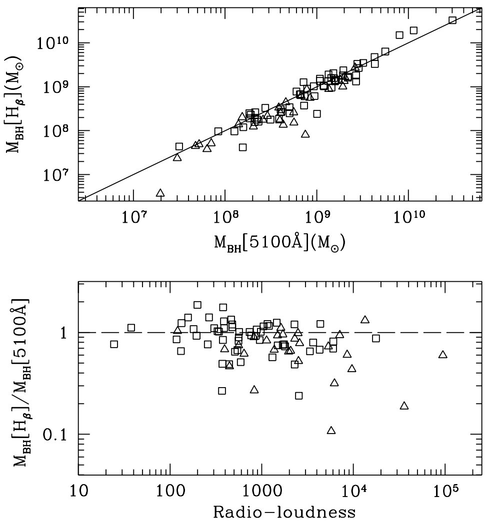

Fig. 2 Upper panel: Comparison of the black hole masses of radio-loud quasars estimated with $R - L_{\mathrm{H}_\beta}$ and $R - L_{5100\mathrm{\mathring{A}}}$ relations. The squares represent 59 quasars in Brotherton (1996) and the triangles represent 27 quasars in Oshlack et al. (2001). The diagonal line shows the results are identical. Lower panel: The ratios of black hole masses estimated with two different relations are plotted against the radio-loudness of radio-loud quasars. The dashed line shows that two black hole masses are identical (Figure taken from Wu et al. 2004).

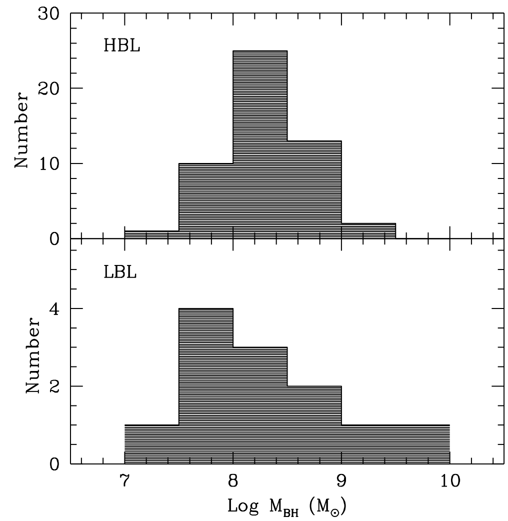

Fig. 3 Histogram of the black hole mass distribution of 51 high-frequency peaked BL Lacs (HBL) and 12 low-frequency peaked BL Lacs (LBL) derived with the fundamental plane relation (Figure taken from Wu et al. 2002).

We have compared the black hole masses obtained for 59 radio-loud quasars in a sample of Brotherton (1996) and 27 radio-loud quasars in a sample of Oshlack et al. (2001) with both the $R - L_{\mathrm{H}_\beta}$ and $R - L_{5100\mathrm{\mathring{A}}}$ relations (see Fig. 2). Evidently the masses obtained with the $R - L_{\mathrm{H}_\beta}$ relation are systematically lower that those obtained with the $R - L_{5100\mathrm{\mathring{A}}}$ relation for some extremely radio-loud quasars (That is the reason why there are so many data points under the diagonal line in the upper panel of Fig. 2). We also investigate the dependence of the difference of two black hole mass estimates on the radio-loudness (see the lower panel of Fig. 2). Clearly the difference of black hole masses becomes larger as the radio-loudness increases. Therefore, Using the $R - L_{\mathrm{H}_\beta}$ relation one can obtain more accurate black hole masses of some extremely radio-loud AGNs.

In addition, a tight correlation between black hole mass and bulge velocity dispersion (σ) has been found for nearby galaxies (Tremaine et al. 2002), and for a few Seyfert galaxies (Ferrarese et al. 2001). This implies that the M_{BH}-σ relation is probably universal for both active and inactive galaxies. Such a tight relation suggests an interesting possibility to estimate the central black hole masses of AGNs using the measured values of central velocity dispersions (Wu & Han 2001a,b). This is particularly helpful to BL Lacertae objects which show very weak or no emission lines so the reverberation mapping can not apply to them. However, AGNs usually have bright nuclear emission, which makes it difficult to measure their central velocity dispersions with the spectroscopic method. It is well known for elliptical that three observables, the effective radius, the corresponding average surface brightness and the central velocity dispersion, follow a surprisingly tight relation (fundamental plane). The elliptical hosts of radio galaxies follow the same fundamental plane as normal ellipticals (Bettoni et al. 2001). The fundamental plane can be robustly described as

$$\log R_e = (1.27 \pm 0.04) \log \sigma + (0.326 \pm 0.007) \langle \mu_e \rangle_R - 8.56 \pm 0.06, \qquad (6)$$

where R_e is the effective radius in kpc, and $\langle \mu_e \rangle_R$ is the average surface brightness in R-band. Because the fundamental plane probably exists also for elliptical hosts of AGNs, this provides a possible way to estimate the central velocity dispersions and the SMBH masses of AGNs. We have adopted the fundamental plane relation to estimate the central velocity dispersion and the black hole mass of 63 BL Lacs in the HST snapshot survey (Urry et al. 2001). Most BL Lacs have black hole masses in the range of $10^{7.5}$ to $10^{9.5}\,M_\odot$ (see Fig. 3 and Wu, Liu & Zhang 2002 for details).

4 RELATIONS OF BLACK HOLE MASS WITH OTHER OBSERVED PROPERTIES

Several relations of black hole mass with other observed properties have been found in microquasars and AGNs. First, the power density spectra of some Seyfert 1 galaxies were found to be similar as black hole X-ray binaries, but with the characteristic frequency about 10^5 times lower. McHardy et al. (2004) found that there seems to be a same scaling law between the black hole mass and the break timescale for both black hole X-ray binaries and AGNs. Narrow line Seyfert 1s seem to correspond to the high state of microquasars, while broad line Seyfert 1s seem to correspond to the low state. Such a relation can be understood if the break time scale is proportional to the black hole mass. Second, a fundamental plane of black hole activity has been found by Merloni et al. (2003) for black hole systems at different scales including both microquasars and quasars. It suggests a somehow universal relation among the radio, X-ry luminosities and black hole mass, which may come from the same accretion physics and jet formation process in these different black hole systems.

5 DISCUSSION

Although at different scales, microquasars and quasars share many similar properties. The analogy between them has been well demonstrated. This also implies that the same physics exists for different black hole accretion systems. The recent progress in determining the black hole masses of both microquasars and AGNs enables us to investigate the relations of black hole masses with other observed properties. These relations include one between the black hole mass and break frequency in the power density spectrum and one among the black hole mass, radio and X-ray luminosities. They may be useful in the future for estimating the black hole masses in microquasars and AGNs.

Besides its relation with timing properties, black hole mass is probably also related to the X-ray spectra properties of microquasars and AGNs. Recently Shrader & Titarchuk (2003) used a disk blackbody plus bulk motion comptonization model to suggest a method to estimate the black hole masses for black hole X-ray binaries, ultra-luminous X-ray sources and narrow line Seyfert 1s. Although it is model dependent, such a method may provide us some helpful information about the black hole mass in ultra-luminous X-ray sources and narrow line Seyfert 1s, which are poorly understood at present. Abramowicz et al. (2004) suggested to detect the high-frequency QPOs in ultra-luminous X-ray sources and AGNs, which can also probably tell us how massive the black holes in these sources are. These efforts may help us to know whether the intermediate mass black holes exist in ultra-luminous X-ray sources.

Finally, one point worthy to mention is that microquasars are all transient X-ray sources. Is there any transient AGN? The answer may be "yes". Indeed, Grupe (2002) has found several transient AGNs by ROSAT X-ray observations. However, the detailed modelling of them and comparisons with microquasars are still expected. Another interesting question is, do different types of AGNs correspond to black hole X-ray binaries in different spectral state? The answer is "likely". Narrow line Seyfert 1s do share many similarities with black hole X-ray binaries in high state, while LINERs and radio-loud quasars may be similar as microquasars in low state. Further studies on these different black hole systems will undoubtedly tell us more about their physics nature.

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