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Probing Quasar Black Hole Evolution through Black Hole Mass Function and Gravitational Waves

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Abstract

We model the optical QSO luminosity functions (LFs) at high redshifts (z>2.2) with the simple assumptions of QSO/supermassive black hole (SMBH) formation in the CDM universe. We use the two model parameters concerning QSO/SMBH formation; one is the "lifetime of QSOs", t_Q and the other is the relations between the halo mass and the SMBH mass. However, we allow several sets of parameters only to fit the LFs and cannot fix the parameters. Here, we represents some methods to break this degeneracy. First, we calculate the mass function of SMBHs at z=2.5 based on models and compare the results with mass function at z=0. As a result, the mass function of the shorter lifetime model ($\sim 10^6$yr) at z=2.5 already exceeds the present one. Therefore, we conclude that the lifetime of QSOs is at least more than 10^7 years. Second, we consider the merger rate of SMBHs. We show that the the difference of merger rate can constrain the models and that the minimum halo mass to possess the SMBHs affects the redshift distribution of the merger rates.

1.1 Introduction

Here, we model the observed optical luminosity functions (LFs) of QSOs at $z > 2.2$ and consider the constraint on the formation/evolution history of QSOs and SMBHs. We use the Press-Schechter formalism for dark halo formation/destruction history, and model the QSOs with simple assumptions. Our approach is similar to Haiman & Loeb (1998) (HL98) and Haehnelt et al. (1998) (HNR98). In our models, model parameters are the lifetime of QSOs, t_Q and the relations between the halo mass and the SMBH mass. As many authors pointed, we allow several sets of parameters only to fit the LFs and cannot fix the parameters. Haiman & Hui (2001) and Martini & Weinberg (2001) show that the QSO clustering is effective tool to discriminate models. We represent other some methods to break this degeneracy. We calculate the mass function of SMBHs and the cosmological merger rates of SMBHs. Especially, we show that the longer lifetime model ($t_Q > 10^7$ yr) is required compared with the mass function of SMBHs estimated at the local universe. Furthermore, we calculate the merger rate with the lower limit of halo mass to possess SMBHs and show that the lower limit considerably affect the redshift distribution of merger rates.

We adopt the ΛCDM cosmology and the cosmological parameters of (Ω_0,Ω_Λ,$\Omega_{\rm b}$,h,$\sigma_{8h^{-1}}$,n) = (0.35, 0.65, 0.04, 0.65, 0.87, 0.96). These results have been already published as

Hosokawa et al. (2001) and Hosokawa (2002) (hereafter Paper I and II). Please see these papers in detail.

1.2 Modeling the QSO Luminosity Functions

Our modeling of QSO LFs is very simple. First, we assume that there is necessarily one SMBHs in one dark halo. The formation rates of dark halos are given by extended Press-Schechter formalism analytically. Second, the mass of SMBHs are given by following 3 relations; (A)$M_{\rm BH} \propto M_{\rm halo}^{5/3} \times (1+z_f)^{5/2}$, (B)$M_{\rm BH} \propto M_{\rm halo}$, (C)$M_{\rm BH} \propto M_{\rm halo}^{5/3}$, where z_f is the formation redshift of the dark halo. Finally, each SMBHs is assumed to radiate as QSOs at Eddington Luminosity during the timescale t_Q since the formation of its host halo. After all, the model parameters are the relations between $M_{\rm BH}$ and $M_{\rm halo}$ and the lifetime of QSOs, t_Q. (see Paper I or II in detail) We adjust these parameters to fit the observed optical QSO LFs at $z > 2.2$. We adopt the model spectrum of QSOs based on disk-corona model by Kawaguchi et al. (2001), then calculate the fraction of the B-band ($4400\mathring{A}$) luminosity to the bolometric luminosity.

The best-fit parameters in each models are listed in table.1. And Fig.1 shows the best-fitted QSO LFs at $z > 2.2$ with these parameters. Observationally, the number density of optically bright QSOs ($M_{\rm B} < -26$) decrease by 1/10 from $z \sim 2$ to $z \sim 4.5$. Our simple model successfully reproduce this tendency.

	t_Q	$M_{\rm BH} - M_{\rm halo}$ relation
A	6×10^7 yr	$\frac{M_{\rm BH}}{10^8 M_\odot} = 0.012 \left(\frac{M_{\rm halo}}{10^{12} M_\odot}\right)^{5/3} (1+z_f)^{5/2}$
B	1×10^6 yr	$\frac{M_{\rm BH}}{10^8 M_\odot} = 1.26 \times 10^{-3} \frac{M_{\rm halo}}{10^{12} M_\odot}$
C	1×10^7 yr	$\frac{M_{\rm BH}}{10^8 M_\odot} = 0.713 \left(\frac{M_{\rm halo}}{10^{12} M_\odot}\right)^{5/3}$

Table 1.1. *Best-fit model parameters in each models.*

1.3 Breaking the Model Degeneracy

As shown in Fig.1, we can successfully reproduce observed QSO LFs in all models. In other words, we cannot constrain model parameters (e.g. t_Q) only fitting the QSO LFs, that is, there is the model degeneracy. Here, we consider why this degeneracy occurs and represent the way to break this degeneracy.

1.3.1 Mass Function of SMBHs

One can interpret why the degeneracy occurs with numerical values of model parameters listed in Table.1. In model A, the QSO lifetime is longer, $t_Q \sim 6 \times 10^7$yr, whereas in model B, t_Q is shorter, $t_Q \sim 10^6$yr. The different t_Q is covered by the different $\epsilon \equiv M_{\rm BH}/M_{\rm halo}$. In model A, $\epsilon \sim 10^{-4 \sim -5}$, whereas in model B, $\epsilon \sim 10^{-3}$. We assume that every QSOs radiate at Eddington luminosity, which is proportional to $M_{\rm BH}$. Therefore, in model A QSOs are long-lived and poor-luminous, meanwhile

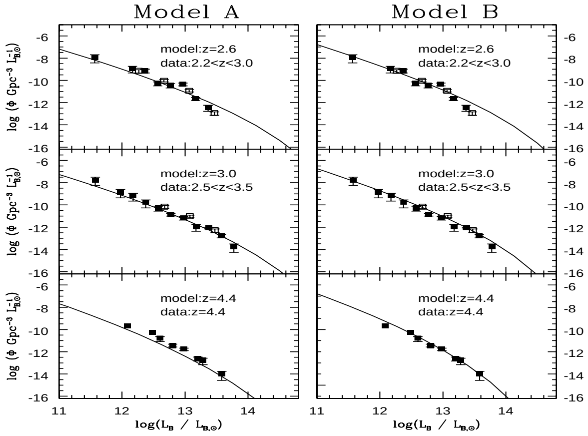

Fig. 1.1. Best-fitted QSO LFs at $z > 2.2$. The left panel represents the results in model A, and the right panel represents in model B. Numerical values of model parameters are listed in Table.1.

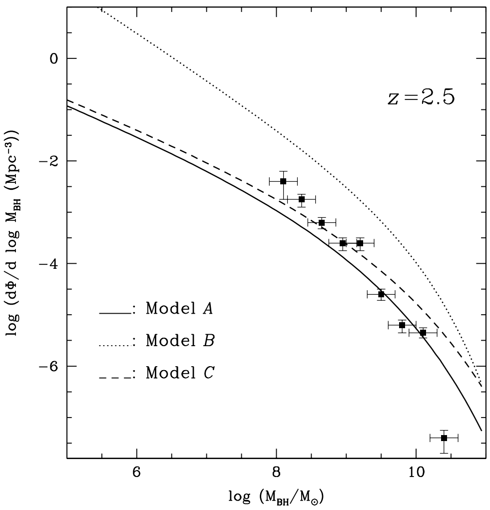

Fig. 1.2. Comparison between calculated mass functions of SMBHs based on each models and estimated present-day mass functions of SMBHs (Salucci et al. 1999).

in model B QSOs are short-lived and rich-luminous. Balancing between the lifetime and luminosity, each models can reproduce the observed LFs.

To break the degeneracy, we can use difference of $M_{\rm BH}/M_{\rm halo}$ in each models. Here, we calculate the mass function of SMBHs. Since $M_{\rm BH}/M_{\rm halo}$ is different, the halo mass corresponding to a given black hole mass is different. The number density of dark halos depends on its mass, then calculated mass functions of SMBHs based on three models are different. Since our simple model is not successful at $z < 2$ same as similar studies (e.g. HL98, HNL98), we calculate the mass function of SMBHs at

$z = 2.5$. Though the mass function of SMBHs at $z \sim 2.5$ is unknown observationally, we can constrain our models even with local mass function of SMBHs (Salucci et al. 1999). Fig.2 shows the results. In model B, the number density of SMBHs at $z = 2.5$ already exceeds the present-day number density considerably. As long as there are not many SMBHs out of the center of galaxies in the local universe, this situation is unrealistic. Thus, we conclude that the lifetime of QSOs is at least $t_Q > 10^7$yr.

1.3.2 Merger Rates of SMBHs

Another way to break the model degeneracy is cosmological merger rates of SMBHs (Haehnelt 1998). Even if a SMBH-SMBH binary merges at cosmological distance, we will be able to reliably detect these events with *LISA* (Laser Interferometer Satellite Anntena) with high S/N ratio. Here, we assume SMBHs merge immediately when its host halos merge. The calculated redshift distribution of the SMBH merger rates are considerably different in each models (We have no figure here. See Haehnelt 1998). This is because the number densities of SMBHs of a given black hole mass are different in each models (see Fig.2). For example, the merger events between $10^7 M_\odot$-$10^7 M_\odot$ SMBHs, in model A we can detect less than 1 time per year, whereas in model B several ten times per year.

1.4 Minimum Halo Mass to Possess SMBHs

We consider the minimum halo mass to possess SMBHs. Whether the minimum halo mass exists or not can constrain the formation scenarios of SMBHs (Ferrarese 2002). Here, we calculate the redshift distribution of merger rates of SMBHs with the minimum halo mass to possess the SMBHs. We adopt two cases of $\sigma \geq 50$km/s ($M_{\rm min} = 10^9(1+z_f/10)^{-3/2} M_\odot$) ($\sigma$ is the velocity dispersion in a halo) and $M_{\rm min} = 2 \times 10^9 M_\odot$ as the minimum halo mass to possess SMBHs. In the most probable model A, these correspond to $M_{\rm BH} > 10^3 M_\odot$, which is the detectability limit of LISA for SMBHs binary.

Fig.3 represents the results. As shown in this figure, the merger rates significantly decrease as $M_{\rm BH}$ decreases with the minimum halo mass. Furthermore, it depends on models how the redshift distribution of the merger rate changes with $M_{\rm BH}$. The redshift distribution of the merger rates is determined by (i) the relation between $M_{\rm halo}$ and $M_{\rm BH}$, (ii) how to prescribe the minimum halo mass to possess the SMBHs, and (iii) the relation between (i) and (ii). Especially, redshift dependence of the relation between $M_{\rm halo}$ and $M_{\rm BH}$ and minimum halo mass is important for how the merger rates decrease as $M_{\rm BH}$ decreases.

1.5 Summary

Here, we briefly summarize our results.

- We can fit the observed optical QSO LFs at $z > 2.2$ with the simple models based on the hierarchical structure formation. We can reproduce the decrease of the number density of QSOs from $z \sim 2-3$ to $z \sim 4.5$.
- We can discriminate models with the mass function of SMBHs or redshift distribution of merger rates. Especially, comparing the mass function of SMBHs at $z = 2.5$ based in our models with the local mass function, we can rule out the

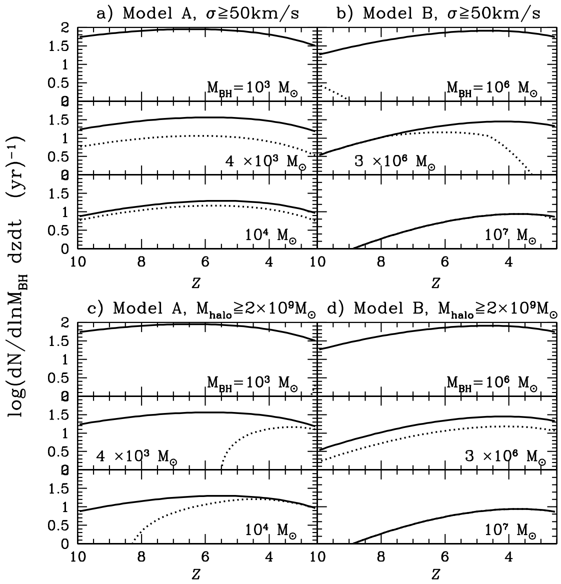

Fig. 1.3. The number of the SMBH mergers which can be detected per year with the halo mass lower limit to possess the SMBHs. The figure a) represents the results of model A with lower limit of $\sigma \geq$ 50km/s, b) model B with $\sigma \geq$ 50km/s, c) model A with $M_{\rm halo} \geq 2 \times 10^9 M_\odot$, and d) model B with $M_{\rm halo} \geq 2 \times 10^9 M_\odot$. In model A, we calculate the major merger rates of SMBHs of $M_{\rm BH} \sim 10^3, 4 \times 10^3$ and $10^4 M_\odot$, whereas in model B, $M_{\rm BH} \sim 10^6, 3 \times 10^6$ and $10^7 M_\odot$. In each panel, the solid and dotted line represent the results without and with the lower limit, respectively. In the top left and top right panels of each figure, dotted lines are hardly seen.

shorter lifetime model (model B). We conclude that the QSO lifetime, t_Q is at least more than 10^7yr.

- Merger rates significantly decrease as $M_{\rm BH}$ decreases with the minimmum halo mass to possess the SMBHs. The redshift distribution of the merger rates depends on both $M_{\rm BH} - M_{\rm halo}$ relations and how to prescribe the minimum halo mass (given by σ or $M_{\rm halo}$).

References

Ferrarese, L. 2002, ApJ, 578, 90

Haehnelt, M.G., Natarajan, P., Rees, M.J., 1998, MNRAS, 300, 817 (HNR98)

Haehnelt, M.G., 1998, in *Second International LISA Symposium*, AIP Conference Proceeding, vol. 456, ed. W.M. Folkner, p.45

Haiman, Z., & Loeb, A. 1998, ApJ, 503, 505 (HL98)

Haiman, Z., & Hui,L. 2001, ApJ, 547, 27

Hosokawa, T., Mineshige, S., Kawaguchi, T., Yoshikawa, K., & Umemura, M. 2001, PASJ, 53, 861 (Paper I)

Hosokawa, T. 2002, ApJ, 576, 75 (Paper II)

Kawaguchi, T., Shimura, T., Mineshige,S. 2001, ApJ, 546, 966

Martini, P., & Weinberg, D.H. 2001, ApJ, 547, 12

Salucci, P., Szuszkiewicz, E., Monaco, P., Danese, L. 1999, MNRAS, 307, 637