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学 位 論 文 要 旨
Dissertation Summary

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論　文　名: Optical Imaging Survey for Low-luminosity Quasars in the Early Universe
(Dissertation Title)

The formation and evolution of supermassive black holes (SMBHs) are important topics in the modern astrophysics for understanding the nuclear activity of galaxies and the total picture of the galaxy formation, because it is now widely recognized that the SMBH evolution is closely coupled with the galaxy evolution (so-called galaxy-SMBH coevolution). Especially, the quasar luminosity function (QLF) provides us a clue to understand the evolution of SMBHs from a statistical viewpoint. Recent quasar surveys in optical and X-ray have derived QLFs at various redshifts over a wide luminosity range. They have suggested that the redshift evolution of the quasar number density is luminosity-dependent. However, the number density of low-luminosity quasars at $z > 4$ is unclear due to the following two reasons. One reason is that the observationally-inferred number density includes possible large systematic errors due to drawbacks in the widely-adopted method for evaluating the survey completeness and the resultant quasar number densities. The other reason is the large statistical error in the quasar number density due to the lack of a sufficient number of low-luminosity quasars at $z > 4$. Therefore in this doctoral dissertation, we revisit the survey completeness and QLF at high redshift with a new method and derive the QLF with a large sample of low-luminosity quasars at high redshift.

In order to derive the number density of low-luminosity quasars accurately at high redshift, we first improve the evaluation method of the number density of low-luminosity quasars. Generally high redshift quasars are selected by using their color properties. Therefore it is important to make realistic model spectra, which well reproduce actual quasar spectra, for simulations to estimate the survey completeness. The survey completeness is usually estimated by adopting a typical template of the quasar spectrum, constructed empirically or based on simple models. However the equivalent width (EW) of broad emission lines in the quasar spectrum strongly depends on the quasar luminosity, in the sense that lower-luminosity quasars show emission lines with a larger EW (the Baldwin effect). If the quasar luminosity investigated in a survey is much lower than that of a template used to estimate the survey completeness, the quasar colors calculated from the template may be systematically different from the actual quasar colors due to the unexpected contribution of emission-line fluxes into broad-band magnitudes. Therefore it is essential to know how the Baldwin effect affects the estimate of the completeness in quasar surveys and the resultant QLFs.

We made composite spectra for each luminosity based on the Baryon Oscillation Spectroscopic Survey (BOSS) quasars and quantified the Baldwin effect. As the result, we found that lower-luminosity quasars at $z \sim 4$ - 5 are more easily selected by color selection criteria than higher-luminosity quasars when the effects of the Baldwin effect are properly considered. Furthermore the correction of the effect of the inter-galactic medium (IGM) absorption is important for preparing realistic model spectra of high redshift quasars. Recently, a new IGM absorption model, which well reproduces recent observational data of the IGM column density, was published. We evaluate the effect of the difference in IGM models for the estimate of the survey completeness by using COSMOS images observed with Subaru / Suprime-Cam. We find that the latest IGM model predicts a smaller Lyman-break feature at $z = 4$ - 5 than older IGM model, which makes the color selection of quasars more challenging.

The results indicate that the completeness estimates are sensitive to the luminosity dependence of the quasar spectrum and also to IGM attenuation models. At $z \sim 4$, the number density of quasars derived with the newly estimated completeness is $(3.49\pm1.62)\times10^{-7}$ Mpc^{-3} mag^{-1} for $-24.09 < M_{1450} < -23.09$ and $(5.24\pm2.13)\times10^{-7}$ Mpc^{-3} mag^{-1} for $-23.09 < M_{1450} < -22.09$, which are ~24% lower than those estimated by the conventional method. On the other hand, at $z \sim 5$, the 1σ confidence upper limit of the number density at $-24.5 < M_{1450} < -22.5$ in the new estimates is ~43% higher than that estimated previously. These results suggest that the luminosity dependence of the quasar spectrum and the IGM model are important for deriving the accurate number density of high redshift quasars.

Secondly we construct a large sample of low-luminosity quasars at $z \sim 5$ to study the statistical evaluation of the number density of quasars, by taking the above results into account. Because of the insufficient area and depth of previous surveys, the low-luminosity quasar survey was difficult. However the strategic survey program of the Subaru telescope with the Hyper Suprime-Cam (HSC-SSP) provides a key solution to search for faint quasars at high redshift. The HSC-SSP wide-field optical imaging survey started in March 2014 and plans to spend 300 nights for 5 years. By taking advantage of the wide field-of-view (FoV) of HSC (a circular FoV with 1.5 deg in diameter), the Wide-layer component of the HSC-SSP survey will cover ~1,400 deg^2 when the survey is completed. The 5σ survey depth of the Wide-layer component reaches ~3 mag deeper than that of the SDSS survey. Thanks to the deep and wide HSC-SSP survey data, we can search faint quasars at high-redshift.

By the new method of the newly established high redshift quasar selection, we construct a large sample of $z \sim 5$ low-luminosity quasars based on the wide survey data in a part of the HSC-SSP. In 81.8 deg^2 area within the Wide layer of the HSC-SSP survey, 224 candidates of low-luminosity quasars at $z \sim 5$ are selected by adopting the Lyman-break method in the magnitude range of $19.1 < i < 24.1$. We derive the QLF at $z \sim 5$ by removing the sample of $M_{1450} > -23.32$, where the sample is largely affected by the contamination of compact galaxies. The resultant binned QLF at $z \sim 5$ is consistent with that of previous studies at $M_{1450} < -24.32$. We fit a double power-law model to our HSC and Sloan Digital Sky Survey (SDSS) sample that is distributed in a wide luminosity range ($-28.76 < M_{1450} < -23.32$) with the maximum likelihood method. In this process, the bright-end slope is fixed to -2.90 based on the number densities of some previous studies for bright quasar samples. As a result, it turn out to be that the best-fit faint-end slope, $\alpha = -1.22^{+0.03}_{-0.10}$, is flatter than that reported by previous studies at $z \sim 5$. The break of the double power-law is fainter and higher number densities than the results of $z \sim 5$ previous studies. This is because our sample covers a wider luminosity range extending enough fainter range than the break luminosity of the double power-law function. Also we investigate the QLF parameters at $3 \leq z \leq 6$ with those in the literature. The HSC results suggest that the faint and bright-end slope and the break luminosity are roughly consistent at $4 \leq z \leq 6$, although other previous studies suggested that the faint-end slope becomes steeper at higher redshifts. Furthermore we explore the redshift evolution of the quasar number density for each luminosity. Our results show that the number density of faint quasars decreases toward high redshift at $z > 3$, similar to bright quasars. This evolution is consistent with the AGN down-sizing scenario. In addition, as indicated by previous studies for luminous quasars,

the number density of low-luminosity quasars also decrease more rapidly from $z \sim 5$ to $z \sim 6$ than from $z \sim 4$ to $z \sim 5$.

Furthermore, we conduct spectroscopic observations for a part of the HSC photometric sample of $z \sim 5$ quasar candidates, and measure properties of their SMBHs. Observed low-luminosity quasars show lower MBH than most SDSS quasars at $z \sim 5$ and relatively high Eddington ratio that is close to the Eddington limit. It suggests that the SMBHs of the sample in this study are in a relatively young phase of the evolution.