論文の内容の要旨

The Size and Luminosity Distributions of Galaxies in the Reionization Era and Their Implications for Galaxy Formation

(再電離期の銀河のサイズと光度および銀河形成へのそれらの示唆)

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The luminosity function and the size–luminosity relation of galaxies are important probes for galaxy formation and evolution. Continuous efforts have been made to investigate these functions and relations at higher redshifts. We construct $z \sim 6-7$, 8, and 9 faint Lyman break galaxy samples (334, 61, and 37 galaxies, respectively) from the complete *Hubble* Frontier Fields (FF) cluster and parallel fields data.

The gravitational lensing effects are calculated using our own mass models of all six HFF clusters with the software `glafic`. We use positions of 132, 202, 173, 108, 141, and 135 multiple images to constrain the matter distributions of Abell 2744, MACS J0416.1−2403, MACS J0717.5+3745, MACS J1149.6+2223, Abell S1063, and Abell 370, respectively. Among them, 182 multiple images are new systems identified in this thesis. We find that our best-fitting mass models reproduce the observed positions of multiple images quite well, with image plane RMS of $\sim 0\farcs4$. For Abell 2744, our best-fitting mass model recovers the observed magnification at the position of the Type Ia supernova HFF14Tom (Rodney et al., 2015). We find that the predicted time delays and flux ratios of the quadruple images of SN Refsdal (Kelly et al., 2015) in MACS J1149.6+2223 are consistent with observations (Treu et al., 2016). All of our mass models are publicly available through the STScI website.

The sizes and magnitudes of the galaxies in the $z \sim 6-9$ samples are carefully measured by a two-dimensional fitting algorithm using a lensing-distorted Sérsic profile. Thanks to the strong gravitational lensing effects, the constructed galaxy samples are the largest hitherto and reach down to the faint ends of recently obtained deep luminosity functions. At faint magnitudes, however, these samples are highly incomplete for galaxies with large sizes, implying that derivation of the luminosity function sensitively depends on the intrinsic size–luminosity relation. We thus conduct simultaneous maximum-likelihood estimation of luminosity function and size–luminosity relation parameters from the observed distribution

of galaxies on the size–luminosity plane with help of a completeness map as a function of size and luminosity. At $z \sim 6-7$, we find that the intrinsic size–luminosity relation expressed as $r_\mathrm{e} \propto L^\beta$ has a notably steeper slope of $\beta = 0.46^{+0.08}_{-0.09}$ than those at $z \sim 4-5$ ($\beta \simeq 0.22$–0.25) and those assumed in previous studies of the luminosity function at $z \sim 6-7$ ($\beta \simeq 0.25$). As a result of the steep size–luminosity relation, a shallow faint-end slope of the luminosity function of $\alpha = -1.86^{+0.17}_{-0.18}$ is derived. The values of β and α at $z \sim 8$ and 9 are consistent with those at $z \sim 6-7$, but have large errors due to small sample sizes. Thus, at $z \sim 8$ and 9, the UV luminosity density is still highly uncertain, which has to be taken into account in the discussion of cosmic reionization.

We quantify the correlation between the parameters of the size–luminosity relation and luminosity function. Among the parameter pairs, we find strong correlations between the faint-end slope of the luminosity function and the slope of the size–luminosity relation, (α, β), and between the faint-end slope and the characteristic magnitude of the luminosity function, (α, $M_\star$). Although the values of α in several previous studies are consistent with our measurements, some of the previous results are found to be located outside our confidence region in the α–β plane.

We construct an analytical model to reproduce the steep slope of the size–luminosity relation at $z \sim 6-7$, utilizing the result of the abundance matching in Behroozi et al., (2013). We find that the steepness is not reproduced when $j_\mathrm{d}/m_\mathrm{d}$ is constant within the magnitude range studied here. One possible explanation for the steepness is that a smaller fraction of the specific angular momentum is transferred to the disk from its halo at fainter magnitudes. Another possible explanation is that low-mass halos can host galaxies only when they have relatively small halo spin parameters.

The average size at $(0.3-1)L^*_{z=3}$ gradually decreases with redshift with $(1+z)^{-m}$, where $m = 1.28 \pm 0.11$ over a redshift range of $4 \lesssim z \lesssim 9.5$. However, we point out that this conventional discussion of the size evolution suffers from systematic biases due to a variance in average luminosity between the samples. In order to overcome this issue, we calculate the disk-to-halo size ratio to find $j_\mathrm{d}/m_\mathrm{d} \sim 1$ at $M_\mathrm{UV} = -21$.

For deeper insights into physical properties of $z \sim 6-9$ galaxies, we investigate their UV colors, multiplicities, and star-formation surface densities (Σ_SFR). These parameters indicate, respectively, the degree of chemical evolution, recent mergers, and the efficiency of star formation. The UV colors are calculated from aperture magnitudes of two bands and the multiplicities are identified by visual inspection. These analyses are the first to incorporate the information of size into discussions of the two parameters at $z \sim 6-9$. The efficiencies of star formation are calculated from their UV magnitudes and sizes. Comparing these efficiencies to those of local galaxies is conducted also for the first time in this thesis. We find that largest ($r_\mathrm{e} > 0.8$ kpc) galaxies are mostly bright and red in UV color while smallest ($r_\mathrm{e} < 0.08$ kpc) ones mostly blue, and that galaxies with multiple cores tend to be bright. The Σ_SFRs of $z \sim 6-9$ galaxies are typically three orders of magnitude higher than those of local normal spiral galaxies. The distribution of our galaxies in the star formation–Σ_SFR plane is largely overlapped with that of circumnuclear star-forming regions in local barred galaxies, which may suggest a similarity in the environment of star formation.