論文の内容の趣旨

Early Stages of Galaxy Formation Probed by Optical Observations and the Machine Learning Technique

(可視光観測と機械学習で探る初期の銀河形成)

提出者氏名：小島 崇史

Hydrodynamical simulation predicts that cluster-like galaxies with low stellar masses ($\sim 10^4$–$10^6 M_\odot$), low metallicities ($\sim$0.1–1% $Z_\odot$), and high specific star-formation rates (sSFR $\sim$ 100 Gyr^{-1}) are formed at $z \gtrsim$ 10–20, and experiencing an early stage of the galaxy formation. Although cluster-like galaxies are important to understand the stellar population and star formation history in the early-stage galaxy formation, data used in previous observational studies are not deep enough to discover cluster-like galaxies.

We have initiated a new survey for local extremely metal-poor galaxies (EMPGs) with Subaru/Hyper Suprime-Cam (HSC) large-area ($\sim$ 500 deg^2) optical images reaching a 5σ limit of $\sim$ 26 magnitude, about 100 times deeper than the one of Sloan Digital Sky Survey (SDSS). To select $Z/Z_\odot < 0.1$ EMPGs from $\sim$ 40 million sources detected in the Subaru images, we first develop a machine-learning (ML) classifier based on a deep neural network algorithm with a training data set consisting of optical photometry of galaxy, star, and QSO models. We test our ML classifier with SDSS objects having spectroscopic metallicity measurements, and confirm that our ML classifier accomplishes 86%-completeness and 46%-purity EMPG classifications with photometric data. Applying our ML classifier to the photometric data of the Subaru sources as well as faint SDSS objects with no spectroscopic data, we obtain 27 and 86 EMPG candidates from the Subaru and SDSS photometric data, respectively.

We conduct optical follow-up spectroscopy for 10 out of our EMPG candidates with Magellan/LDSS-3+MagE, Keck/DEIMOS, and Subaru/FOCAS, and find that the 10 EMPG candidates are star-forming galaxies at $z = 0.007 - 0.03$ with large Hβ equivalent widths of 104–265 Å, stellar masses of $\log(M_\star/M_\odot)$=5.0–7.1, and high specific star-formation rates of $\sim$300 Gyr^{-1}, which are similar to those of early galaxies at $z \gtrsim 6$ reported recently. We spectroscopically confirm that 3 out of 10 candidates are truly EMPGs with $Z/Z_\odot < 0.1$, one of which is HSC J1631+4426, the most metal-poor galaxy with $Z/Z_\odot = 0.019$ so far identified ever.

The number density of our metal-poor galaxies is $\sim 10^{-4}$–10^{-5} Mpc^{-3}, suggesting that such metal-poor galaxies are very rare in the local universe. Our metal-poor galaxies reside relatively isolated environment (i.e., nearest neighborhood distances $\sim$ 3.83 Mpc in median), which is confirmed by a Kolmogorov-Smirnov test ($p = 1.9 \times 10^{-3}$).

We find that α-element ratios of Ne/O and Ar/O show almost constant values of log(Ne/O)~ -0.8 and log(Ne/O)~ -2.4, respectively, while low N/O ratios, log(N/O)$\lesssim -1.4$, suggest the undergoing primary nucleosynthesis due to their low metallicity and young stellar population. Two EMPGs show Fe/O ratios 0.5–1.0 dex higher than Galactic stars and the Fe/O evolution model calculation at fixed metallicity, including the EMPG with the solar Fe/O ratio and 0.019 (O/H)$_\odot$. We conclude that the high Fe/O ratios are attributed to SNe of very massive stars above 300 $M_\odot$.

To probe ionizing radiation in our metal-poor galaxies, we inspect emission lines of Hβ, [O II]3727, [Ar III]4740, [O III]5007, [Ar IV]7136, and He II4686 lines, which are sensitive to ionizing photon in the range of 13.6–54.4 eV. We find that interstellar medium of our metal-poor galaxies is highly ionized characterized by strong [O III]5007, [Ar IV]7136, and He II4686 emission lines. High mass X-ray binary (HMXB) models explain He II4686 intensities of half of our metal-poor galaxies, including ones in very early phases of HMXB evolution ($\lesssim$5 Myr) before or in the middle of the first compact object formation. The other half of our metal-poor galaxies, including two EMPGs of $Z/Z_\odot < 0.1$, are not explained by either the HMXB models or the latest binary stellar synthesis models, where their high He II4686/Hβ ratios are not reproduced at their very young ages, $\lesssim$5 Myr suggested by EW$_0$(Hβ)>100 Å. To explain strong He II4686 emission from very young, metal-poor galaxies, we newly suggest possibilities of metal-poor AGNs and very massive stars beyond 300 $M_{\odot}$. Especially, EMPGs might be able to form very massive star beyond 300 $M_{\odot}$ due to their extremely metal-poor gas, which eventually form intermediate-mass black holes and thus HMXBs as early as ∼2 Myr. To verify our scenarios, self-consistent HMXB modeling is necessary with a higher maximum stellar mass cut above ∼300 $M_{\odot}$.