論文内容の要旨

論文題目：

Exploring the Evolution of Massive Star-forming Galaxies in the Redshift Desert

(赤方偏移砂漠にある大質量星形成銀河の進化の探究)

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We have studied evolution of massive star-forming galaxies in the redshift desert, $1.4 < z < 2.5$, based on NIR spectra, primarily targetting on Hα emission line from BzK-selected star-forming galaxies ($sBzK$s).

In total 27 specta of $sBzK$s were obtained with OHS/CISCO on Subaru Telescope and SINFONI on VLT. We detected Hα emission line from 10 $sBzK$s at the redshift of $z = 1.53$–2.40 with Hα flux in the range of $f(\mathrm{H}\alpha) = (7.4\text{–}49) \times 10^{-17}$ $\mathrm{ergs\,s^{-1}cm^{-2}\AA^{-1}}$. Combining H$\alpha$ fluxes with broad band SEDs, we derived stellar masses of $\log(M_\star/M_\odot) = 10.2$–$11.6$, dust extinctions of $E(B-V) = 0.15$–0.65, and extinction corrected SFRs in the range of 60–1370 $M_\odot\,\mathrm{yr}^{-1}$. Further we derived gas-phase oxygen abundances from [N II]/Hα emission line ratios, and the resulting metallicities range in $12 + \log(\mathrm{O/H}) = 8.6$–$9.3$, most of which is larger than the solar oxygen abundance. In addition, we estimated dynamical masses of individual $sBzK$s and dynamical masses of $\log(M_{\mathrm{dyn}}/M_\odot) = 10.6$–$11.7$ are yielded. Resulting dynamical masses of $sBzK$s are compared with those of other galaxy populations at $z \simeq 2$, such as DRGs, LBGs, and SMGs, and we find that dynamical masses of

$sBzK$s are more consistent with DRGs and SMGs, while they are in average about factor of 10 larger than those of LBGs at $z \simeq 2$.

The mass-metallicity (M-Z) relation of $sBzK$s is examined. M-Z relation of $sBzK$s are found in the sense that massive galaxies tend to be metal-rich, though it is weak. We further compare them with the M-Z relation at $z = 0.1$ and $z \simeq 0.7$, adding further $z \simeq 2$ galaxies from the literatures. In the comparison, it is essential to use the identical calibrations of metallicity and stellar mass, thus we take intensive care to derive each quantity. About half of present $sBzK$ sample has similar metallicities inferred from the local relation which is consistent with DRGs, while the remaining $sBzK$s have lower metallicities consistent with LBGs. All but one galaxies in present sample at $z \simeq 2$ have stellar masses in the narrow range of $10.5 \lesssim \log M_\star/M_\odot \lesssim 11.5$, with large scatter in metallicity. This resembles in "turn-off" region seen in the M-Z relation at $z \simeq 0.7$. The turn-off in the M-Z relation at $z \simeq 0.7$ locates around $\log M_\star/M_\odot \simeq 10.3$, while $z \simeq 2$ galaxies show it at $\log M_\star/M_\odot \simeq 11$, which indicates that active star-formation at $z \simeq 2$ takes place at more massive galaxies than $z \simeq 0.7$. This finding is consistent with "down-sizing" evolution of galaxy in which massive galaxies form their stars at earlier epoch.

Then we examined the relation between specific SFR (SSFR) and stellar mass. $sBzK$s as well as DRGs/LBGs/SMGs have significantly higher SSFR than the local relation from SDSS at a fixed mass. Among these $z \simeq 2$ populations, SMGs are paticularly higher SSFR, which might indicates that instantaneous burst are being induced by violent dynamical phenomena such as major mergers. Compared with SSFRs at $z = 0.1$, these higher SSFRs of galaxies at $z \simeq 2$ indicate that they are acquiring most of their stellar mass at this epoch.

We compared these observed scaling relations with model predictions from PÉGASE.2. Simple and infall models are assumed with varying star-formation and infall time scales. The observed trends of $z \simeq 2$ galaxy population are well explained simultaneously by models with short time scale, $\tau_{\rm sf} = 100$ Myr and initial galaxy total mass of $10^{11} < M_\star/M_\odot < 10^{12}$, while models with longer time scale cannot reproduce the observed trends. This resulting range of age is in fact consistent with the epoch of galactic wind to explain the CM relations of the Virgo and Coma clusters.

Finally $sBzK$s as well as other galaxy populations at $z \simeq 2$ were compared with elliptical galaxies in the Fornax cluster through [Fe/H]$-\log\sigma$ relation. Conversion from gas metallicity to stellar metallicity is carried with model tracks since conversion is almost independent of star-formation history and assumed IMF so far as one-zone models are assumed. The resulting [Fe/H]-$\log\sigma$ relation of $z \simeq 2$ galaxies are almost identical to that of elliptical galaxies in the Fornax cluster. Therefore in terms of stellar metallicity, it is indicated that $sBzK$s and other $z \simeq 2$ galaxies could be almost fully assembled even at $z \simeq 2$.

With the knowledge on the clustering strength and number/mass densities of $sBzK$s from optical/NIR imaging data together with FIR properties from MAMBO observations, properties of $sBzK$s are characterized by: large stellar mass, active star-formation with short time scale but bright K-band flux, metal-rich both in gas and star, strong clustering, and enough number density to accout for local massive ellipticals if combined with $pBzK$s. From these observational results, we would conclude that $sBzK$s are likely to be a progenitor of massive early-type galaxies at $z = 0$.

Although relatively unbiased nature of BzK-selection and scatter in the M-Z relation indicate that various evolutionary phases could be mixed in the $sBzK$ sample, this scatter may give us a hint to an evolutionary scenario in which a massive metal-poor $sBzK$ experiences vigorous starburst phase from now on, then becomes the submillimeter brightest phase induced by major mergers with significant metal production, and finally gets on the local M-Z relation as normal $sBzK$ galaxies. This could occur in the time scale less than 1 Gyr, and after that time scale passed, star-formation could quenched by strong feedbacks such as SNe driven winds and/or AGN heating. Here transition from an $sBzK$ to a passive early-type galaxy would achieved, which could name as the the evolutionary transition of massive galaxies.