論文の内容の要旨

Probing the Evolution of Massive Galaxies with Millimeter-wave Emission Lines
(ミリ波輝線を用いた大質量銀河の進化の調査)

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Spectroscopic observations of galaxies in the distant universe provide essential information for elucidating their formation and evolution. This is especially relevant to the most massive galaxies with stellar mass $\gtrsim 10^{11} M_{\odot}$ because they have been actively forming stars at $z \sim 2$–3, a period called cosmic noon. Historically, spectroscopy of high-redshift galaxies has been done mainly in optical and near-infrared bands. Such observations are very time-consuming, and more importantly, may suffer from the heavy dust obscuration in high-redshift dusty star-forming galaxies. Emission lines at millimeter (mm)/submillimeter (submm) wavelength provide a window to overcome the dust extinction and look into the structure of these galaxies during their assembly phase. In the past two decades, much progress has been made in both observations of mm/submm emission lines from high-redshift galaxies and theoretical works for the interpretation of the results. However, targeted mm line surveys may have biased samples, and only one blind mm line survey with detailed source characterization exists. It is unclear whether the preselection of targeted surveys will affect the results. It is also unknown if there is any type of galaxies overlooked by previous surveys, and the nature of mm line-selected galaxies is waiting to be explored. In this thesis, we present an analysis of five massive distant galaxies discovered by the detection of emission lines in ALMA spectral scan observations of the SSA22-AzTEC26 and VV114 fields. The goals are (1) presenting new mm line searches (2) investigating the physical properties of mm line emitters and discussing galaxies missed before.

We first experiment with line search algorithm using the ALMA Band 3 spectral scan observation of the SSA22-AzTEC26 field. In addition to the targeted submm galaxy SSA22-AzTEC26, we detect four new line emitters with signal-to-noise ratio > 5.2 in the spectral cube smoothed with a 300 km s^{-1} FWHM Gaussian filter. Based on photometric redshifts from UV-to-FIR spectral energy distribution modeling, we reveal that two of them are CO(2–1) at redshifts of 1.113 and 1.146 and one is CO(3–2) at $z = 2.124$. The three sources

are massive galaxies with a stellar mass $\gtrsim 10^{10.5} M_\odot$, but have different levels of star formation. Two lie within the scatter of the main sequence (MS) of star-forming galaxies at $z \sim 1$–2, and the most massive galaxy lies significantly below the MS. However, all three sources have a gas fraction within the scatter of the MS scaling relation, suggesting star formation suppression in the presence of a large gas reservoir.

For the other two line-emitting galaxies in the VV114 field with shallower ALMA data, we exploit the recently released JWST NIRCam/MIRI images. One of the two galaxies, J0107a, is a bright ($\sim$ 8 mJy at observed-frame 888 μm) and ultramassive (stellar mass $\sim 4.5 \times 10^{11} M_\odot$) dusty star-forming galaxy at $z = 2.467$. The JWST NIRCam images of J0107a show a grand-design spiral with a prominent stellar bar extending $\sim$ 15 kpc. The ALMA Band 7 continuum map reveals that the dust emission originates from both the central starburst and the stellar bar. 3D disk modeling of the CO(4–3) emission line indicates a dynamically cold disk with rotation-to-dispersion ratio $V_{\rm max}/\sigma \sim 8$. The other galaxy, J0107b at $z = 2.310$ with a stellar mass of $\sim 1.6 \times 10^{11} M_\odot$ shows spiral structure. Both galaxies are on the MS, but the gas depletion is faster in J0107a, suggesting the effect of the stellar bar. In addition, using photometric redshift, we identify CO(2-1) emission line from a $z = 1.186$ spiral galaxy near J0107a, which is also on the MS.

The results show that untargeted mm/submm line surveys, which blindly select galaxies based on their molecular gas masses, mainly pick massive star-forming galaxies on the MS (4/5 of the sample). The consistency with various scaling relations means our knowledge of gas-regulated galaxy evolution in the distant universe based on optical/NIR galaxy catalogs and targeted CO line follow-up observations is mostly robust. However, the discovery of a possible gas-rich quiescent galaxy in the SSA22-AzTEC26 field suggests targeted line surveys may indeed miss certain types of galaxies which they are biased against. The analysis of J0107a/J0107b shows that a multiwavelength analysis including mm/submm emission line reveals plenty of information about the internal physical processes in star-forming galaxies at cosmic noon and possible nonmerger origin of some of the brightest submm galaxies. We conclude that new mm/submm emission line survey can be conducted using existing spectral scan data, and such studies significantly contribute to our understanding of gas-regulated galaxy evolution at high redshift.