High-resolution ALMA Observations of SDP.81. II. Molecular Clump Properties of a Lensed Submillimeter Galaxy at $z = 3.042$

HATSUKADE, Bunyo (NAOJ)
TAMURA, Yoichi (University of Tokyo)
IONO, Daisuke, MATSUDA, Yuichi, HAYASHI, Masao (NAOJ)
OGURI, Masamune (University of Tokyo)

Deep and wide-field submillimeter surveys have uncovered dust-obscured star-forming galaxies at high redshift (referred to as submillimeter galaxies; SMGs). SMGs have intense star-forming activity with star-formation rates (SFRs) of a few $100-1000\,M_\odot\,\mathrm{yr}^{-1}$, which could be triggered by gas-rich galaxy mergers. SMGs and local ultra-luminous infrared galaxies are known to be on the same relation on the molecular gas mass–far infrared (FIR) luminosity plane ($M_{\mathrm{H_2}}$–L_{FIR}) or molecular gas surface density–SFR surface density plane ($\Sigma_{\mathrm{H_2}}$–Σ_{SFR}), so-called 'burst sequence' high above that of 'normal' star-forming galaxies at local and $z \sim$ 1–3 universe. In order to investigate the star-forming properties of SMGs, spatially resolved observations of molecular gas are essential. However, only a handful of studies exists due to the limited spatial resolution and sensitivity of existing instruments.

We studied spatially-resolved properties of molecular gas and dust in a gravitationally-lensed SMG H-ATLAS J090311.6+003906 (SDP.81) at $z = 3.042$ revealed by the Atacama Large Millimeter/submillimeter Array (ALMA) [1]. We identified 14 molecular clumps in the CO(5–4) line data. The surface density of molecular gas and star-formation rate of the clumps are more than three orders of magnitude higher than those found in local spiral galaxies (Figure 1). The clumps are placed in the 'burst' sequence in the $\Sigma_{\mathrm{H_2}}$–Σ_{SFR} plane, suggesting that $z \sim 3$ molecular clumps follow the star-formation law derived for local starburst galaxies. With our gravitational lens model [2], the positions in the source plane are derived for the molecular clumps, dust clumps, and stellar components identified in the *Hubble Space Telescope* image. The molecular and dust clumps are confined within a ~2 kpc region, while the spatial extent of the stellar components is as large as ~6 kpc and offset toward the west. The molecular clumps have a systematic velocity gradient in the north-south direction, which may indicate a rotating gas disk. One possible scenario is that the components of molecular gas, dust, and stars are distributed in a several-kpc scale rotating disk, and the stellar emission is heavily obscured by dust in the central star-forming region. Alternatively, SDP.81 can be explained by a merging system, where dusty starbursts occur in the region where the two galaxies collide, surrounded by tidal features traced in the stellar components.

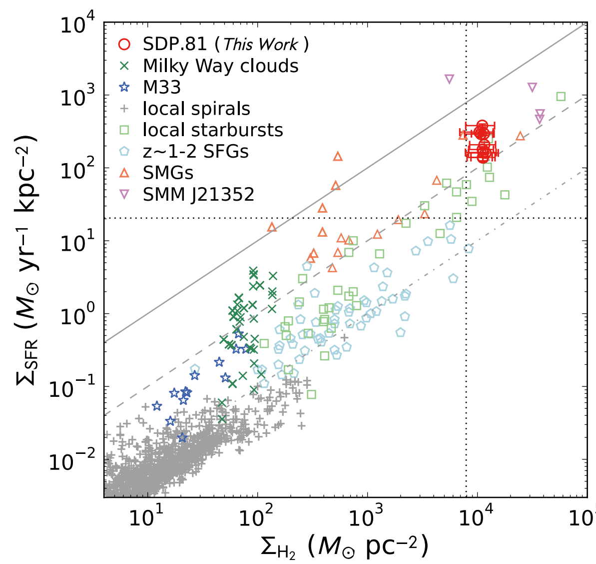

Figure 1: Molecular gas surface density–SFR surface density plot [1]. The molecular clumps of SDP.81 are plotted as red circles. The vertical and horizontal dotted line represents the 2σ detection limit on the surface density of molecular gas and SFR, respectively, for a clump with a source size comparable to the beamsize. For comparison we also plot data points taken from literature: Milky Way clouds, giant H II regions in M33, local disk galaxies, local starbursts, $z \sim$ 1–2 star-forming galaxies, SMGs, and a spatially-resolved lensed SMG SMM J21352. The solid, dashed, and dot-dashed lines represent the gas depletion time scale of 10 Myr, 100 Myr, and 1 Gyr, respectively. If the filling factor is less than unity, the data points of SDP.81 shift to the upper-right direction.

References

[1] Hatsukade, B., Tamura, Y., Iono, D., et al.: 2015, *PASJ*, **67**, 93.
[2] Tamura, Y., Oguri, M., Iono, D., et al.: 2015, *PASJ*, **67**, 72.