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Investigating AGN/Starburst activities through ALMA multi-line observations in the mid-stage IR-bright merger VV 114

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Abstract. We present ALMA cycle 0 observations of the luminous merger VV 114. One of the main goals is to investigate mechanisms of molecular line ratio enhancement. Regions with the high ^{12}CO (1–0)/^{13}CO (1–0) and ^{12}CO (3–2)/^{12}CO (1–0) is located at a central filamentary structure ($\sim$ 6 kpc) in VV 114. The filament consists of the eastern nucleus and the overlap region, where the galaxy disks are colliding. We also investigate these molecular line ratios on the Kennicutt-Schmidt law. VV 114 fills a gap between the "starburst" sequence and the "normal disk" sequence, and regions with the high ratios show the high $\Sigma_{\rm SFR}$ and $\Sigma_{\rm H_2}$. We suggest that the high ratios in VV 114 are due to star-forming activities in the both progenitor's nuclei and the merger-induced overlap region.

Keywords. galaxies: interaction - galaxies: starburst - ISM: molecules

1. Introduction

Molecular line ratios are important diagnostic tools of physical and chemical properties of extragalactic objects (Aalto 2007; Imanishi & Nakanishi 2014). ^{12}CO (3–2)/^{12}CO (1–0) line ratio ($R_{3-2/1-0}$) can trace conditions of molecular gas excitation (temperature and density) directly (Papadopoulos *et al.* 2012), while ^{12}CO (1–0)/^{13}CO (1–0) line ratio ($R_{12/13}$) is observationally known as a tracer of starburst activities (Casoli *et al.* 1992). Although many observations were carried out to understand the enhancement of these ratios in luminous galaxies (e.g., Casoli *et al.* 1992; Aalto *et al.* 1995; Glenn & Hunter 2001; Papadopoulos *et al.* 2012), the limited angular resolution and sample size (e.g., Aalto *et al.* 1997; Sliwa *et al.* 2012) prevent us from obtaining a detailed understanding of the physics behind the line ratio enhancement. We observed these molecular line ratios with high resolution cycle 0 ALMA (0".5 – 2".0) to investigate gas conditions in

VV 114 and the connection between gas and star-forming activities on the sky and the Kennicutt-Schmidt law (Kennicutt 1998).

VV 114 is a nearby ($D_{\rm L}$ = 82 Mpc) gas-rich ($M_{\rm H_2} = 5.1 \times 10^{10}$ $M_\odot$, Yun *et al.* 1994) interacting LIRG ($L_{\rm IR} = 4.7 \times 10^{10}$ $L_\odot$, Armus *et al.* 2009). An obscured AGN in the eastern galaxy is revealed by mid-IR spectroscopy, X-ray, and submm molecular line observations (Alonso-Herrero *et al.* 2002; Grimes *et al.* 2006; Iono *et al.* 2013), suggesting that both starburst and AGN activities might have been triggered by the ongoing merger.

2. Observations and Results

Observations toward VV 114 were carried out as the ALMA cycle 0 program (ID = 2011.0.00467.S; PI = D. Iono) using fourteen – twenty 12 m antennas. The synthesized beam size of band 3 ($\nu_{\rm obs} \simeq$ 110 GHz) and band 7 ($\nu_{\rm obs} \simeq$ 345 GHz) are 1" – 2" and 0".5, respectively. Although we made images of 10 molecular lines and continuum emission (Iono *et al.* 2013; Saito *et al.* 2013), we present the ^{12}CO (1–0) and ^{13}CO (1–0) images here.

Integrated intensity maps of the ^{12}CO (1–0) and the ^{13}CO (1–0) are shown in Fig. 1a and 1b, respectively. The ^{12}CO (1–0) emission traces northern and southern arm-like features ($\sim$ 12 $\times$ 10 kpc) and the strongest peak does not coincide with the both nuclei, but is located at the overlap region. The two arms coincide with dust lanes (Fig. 1e). On the other hand, the ^{13}CO (1–0) emission shows a filamentary structure ($\sim$ 6 kpc) at the CO centroid of VV 114. The ^{13}CO filament coincides with the Paschen alpha emission (Fig. 1f, Tateuchi *et al.* 2012). This means that the ^{13}CO line is a better tracer of star-forming activities than the ^{12}CO (1–0) line.

2.1. *Line Ratios on the sky*

Spatial distributions of the $R_{3-2/1-0}$ and $R_{12/13}$ in VV 114 are shown in Fig. 1c and 1d, respectively. The northern and southern arms show the low $R_{3-2/1-0}$ and $R_{12/13}$ (0.2 – 0.5 and < 10), while the both nuclei and the overlap region show the high ratios (0.5 – 0.8 and 20 – 50), respectively. The eastern nucleus shows the highest $R_{3-2/1-0}$ ($\sim$ 0.8), while the lower $R_{3-2/1-0}$ is measured near the western nucleus ($\sim$ 0.4). The difference may be due to a presence of strong heating sources. The $R_{3-2/1-0}$ of VV 114 is consistent with that of the early-stage merger, the Antennae (Ueda *et al.* 2012). Iono *et al.* (2013) found an obscured AGN and nuclear starbursts in the eastern galaxy using dense gas tracers (HCN and HCO^+), while the western galaxy only shows extended star formation (Grimes *et al.* 2006; Tateuchi *et al.* 2012).

2.2. *Line Ratios on the Kennicutt-Schmidt law*

The Kennicutt-Schmidt law with the line ratios is shown in Fig. 2a and 2b. Generally, we can see that star-forming regions in VV 114 fill a gap between two sequences ("starburst" and "normal disk", Daddi *et al.* 2010). VV 114 may be in a transition phase from spirals to a luminous merger. Highly excited regions in VV 114 ($R_{3-2/1-0} > 0.6$) already show gas concentrations and intense star-forming activities, while diffuse gas along with the arms is inactive. Similarly, the high $R_{12/13}$ regions also show active star formation.

3. Conclusions

We investigate molecular line ratios ($R_{3-2/1-0}$ and $R_{12/13}$) in the luminous merging galaxy VV 114 with cycle 0 ALMA. Both ratios are elevated (0.5 – 0.8 and 20 – 50,

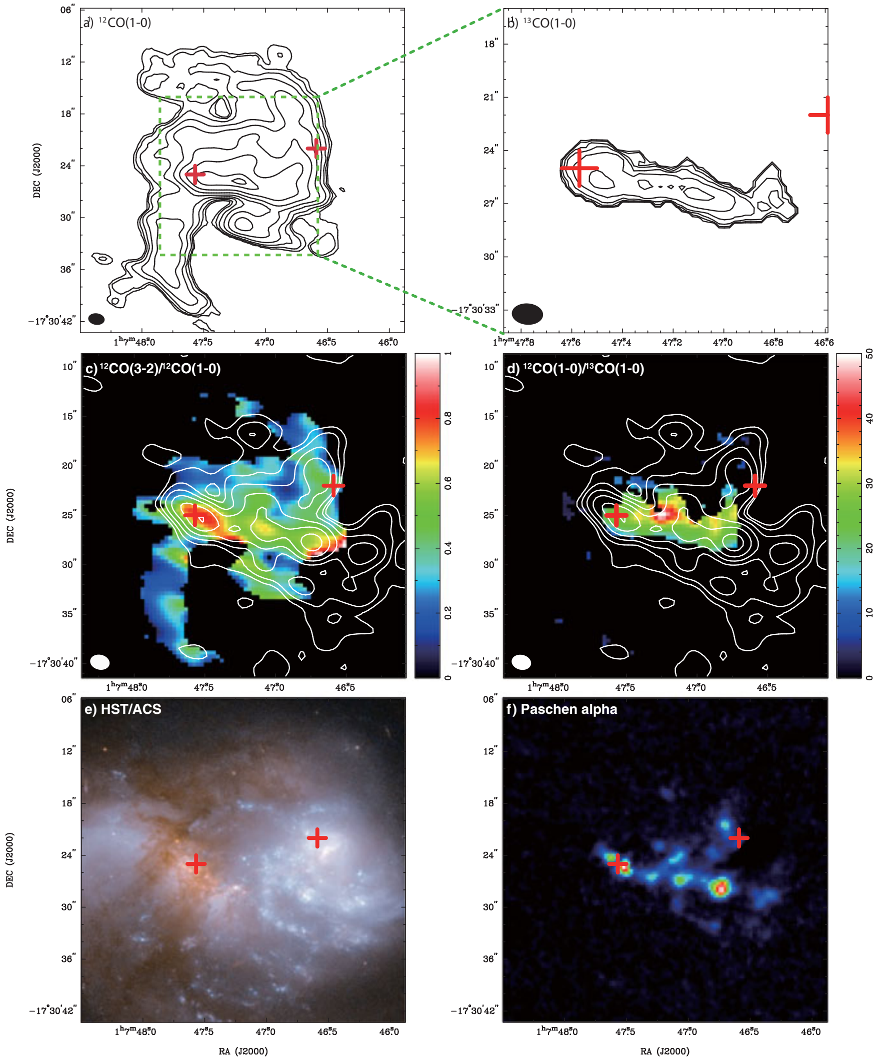

Figure 1. (a) ^{12}CO (1–0) integrated intensity image of VV 114. The red crosses show the positions of the nuclei defined by the peak positions of the Ks-band observation (Tateuchi *et al.* 2012). The black ellipse is the synthesized beam. (b) ^{13}CO (1–0) integrated intensity image of VV 114. (c) The $R_{3-2/1-0}$ image. The contour is the Paschen alpha image. The ratio in color scale ranges from 0 to 1. (d) The $R_{12/13}$ image. The ratio in color scale ranges from 0 to 40. (e) HST/ACS image of VV 114 (Credit: NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University). (f) Paschen alpha image of VV 114 obtained with miniTAO/ANIR (Tateuchi *et al.* 2012).

respectively) in the overlap region as well as the progenitor's nuclei. Moreover, intense star-forming regions (with high gas surface density) show the elevated ratios. We suggest from the distribution of the ratios on the sky and the Kennicutt-Schmidt law that the elevated $R_{3-2/1-0}$ and $R_{12/13}$ are due to star-forming activities. Details will be provided in an upcoming paper (Saito *et al.* 2014 in prep.).

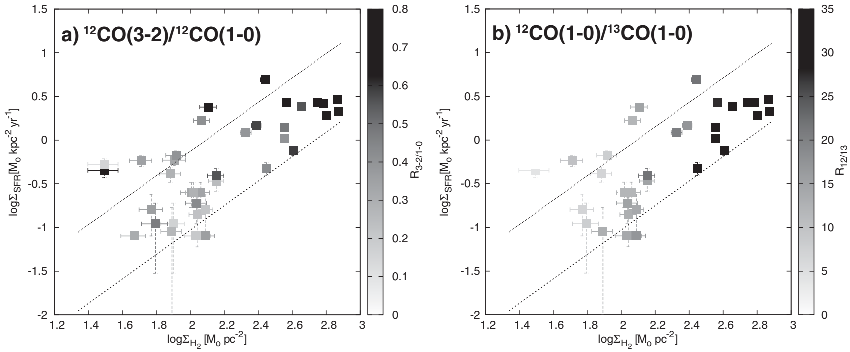

Figure 2. (a) The Kenniccutt-Schmidt law with the $R_{3-2/1-0}$. The ratio in grey scale ranges from 0 to 0.8. The dashed and dotted lines are the "starburst" sequence and "normal disk" sequence, respectively (Daddi *et al.* 2010). (b) The Kennicutt-Schmidt law with the $R_{12/13}$. The ratio in grey scale ranges from 0 to 40.

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