Investigating AGN/starburst activities through ALMA multi-line observations in the mid-stage IR-bright merger VV114

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INTRODUCTION
Most of luminous galaxies (U/LIRGs) are merging galaxies. AGN/starburst activities are triggered by galaxy collisions.

High sensitivity and resolution observations of molecular gas are required!

Teyssier+10; Kartaltepe+10, Hopkins+13
CO/$^{13}$CO line ratios using single-dishes

-~ 5: Galactic GMCs

-10 - 15: normal starburst galaxies

-> 20: luminous mergers (U/LIRGs)

$R_{12/13}$ due to optical depths and/or abundances

Which one is important in U/LIRGs?

We need to know...

- Gas distributions
- Excitation temperature $\sim T_{\text{ex}}$
- Turbulent motion $\sim \sigma_v$
- Column density ratio $\sim N_{\text{co}}/N_{13\text{co}}$

Toshiki Saito, IAU309
The "starburst" sequence and "normal disk" sequence.

Mergers will pass through the gap. $\Rightarrow$ resolved properties?

Kenicutt+98, Daddi+10, Genzel+10, Bournaud+11, Lada+12, Leroy+13
AGN/SB activities in the mid-stage merger VV114

$D_L = 86 \text{ Mpc (} z = 0.02)\$

$L_{\text{FIR}} = 4.1 \times 10^{11} \ L_{\text{sun}} \ (\text{LIRG})$

$M_{\text{gas}} = 5.1 \times 10^{10} \ M_{\text{sun}}$

nuclear separation = 6 kpc

SFR $\sim 45 \ M_{\text{sun}}/\text{yr}$

Distributions of molecular line ratios in VV114?

AGN candidate

Soifer+87; Yun+94; Grimes+06; Evans+08; Tateuchi+12; Iono+13
OBSERVATIONS & RESULTS
## Cycle 0 ALMA observations (P.I. D. Iono)

<table>
<thead>
<tr>
<th></th>
<th>rest freq. [GHz]</th>
<th>obs. time [min.]</th>
<th>angular res. [arcsec.]</th>
<th>$n_{\text{crit}}$ [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(1-0)</td>
<td>115.27</td>
<td>81</td>
<td>2.0 × 1.3</td>
<td>4.1 × 10$^2$</td>
</tr>
<tr>
<td>$^{13}\text{CO}(1-0)$</td>
<td>110.20</td>
<td>61</td>
<td>1.8 × 1.2</td>
<td>1.5 × 10$^3$</td>
</tr>
<tr>
<td>CO(3-2)</td>
<td>345.80</td>
<td>200</td>
<td>1.3 × 1.0</td>
<td>8.4 × 10$^3$</td>
</tr>
<tr>
<td>HCN(4-3)</td>
<td>354.51</td>
<td>203</td>
<td>0.44 × 0.36</td>
<td>8.5 × 10$^6$</td>
</tr>
<tr>
<td>HCO$^+$ (4-3)</td>
<td>356.73</td>
<td>203</td>
<td>0.45 × 0.39</td>
<td>1.8 × 10$^6$</td>
</tr>
</tbody>
</table>

Band 3 & Band 7
fourteen - twenty 12m antennas
compact & extended configurations

10 molecular lines, 110 GHz, and 340 GHz continuum!!

Diffuse gas in VV114 (T. Saito et al. 2013)

Integrated intensity ~ 800 resolution

velocity field

Dust lane (tidal arm)

15 kpc

7.5 kpc
Other lines and continuum (T. Saito et al. 2014 in prep.)

- CN($1_{3/2}-0_{1/2}$)
- CN($1_{1/2}-0_{1/2}$)
- CH$_3$OH($2_k-1_k$)
- CS($2-1$)
- HCO$^+$(4-3)
- HCN(4-3)
- 110 GHz
- 340 GHz (low res.)

$R_{3-2/1-0}$ on the sky and the KS law

$\frac{\text{CO}(3-2)/\text{CO}(1-0)}{R_{3-2/1-0}}$

- 0.2 - 0.5 @arms
- 0.5 - 0.8 @nuclei and overlap
  (normal spirals = 0.2 - 0.5)

Consistent with Lada’s statement

High $R_{12/13}$
- between the progenitors

VV114 fill the gas in the KS.

Keniccutt+98, Komugi+05, Onodera+10, Genzel+10, Warren+12, Leroy+13
\( R_{12/13} \) on the sky and the KS law

\[
\frac{\text{CO}(1-0)}{^{13}\text{CO}(1-0)}, \ R_{12/13}
\]

\[
= 5 - 10 \ @\text{both arms}
\]

\[
= 10 - 20 \ @\text{both nuclei}
\]

\[
= 20 - 50 \ @\text{overlap region}
\]

\textbf{Unusually high } \( R_{12/13} \)

- in the nuclei and overlap
- associate with SF activities

Keniccutt+98, Aalto+05, Komugi+05, Onodera+10, Genzel+10, Leroy+13
Conclusion

Distribution of molecular line ratios in VV114?

1. Distribution on the sky
   - The central filament shows extremely high $R_{3-2/1-0}$ and $R_{12/13}$.
   - Tidal tails show moderate values. (higher than local spiral)

2. Distribution on the Kennicutt-Schmidt law
   - VV114 fill the gap between “starburst” and “normal disk” sequences
   - $R_{3-2/1-0}$ values strongly correlate with the $\Sigma_{SFR}$ (with the SFE slightly).
   - High $R_{12/13}$ may be due to SF activities (see also Saito+14 in prep.).

VV114 will evolve into a “starburst” galaxy!

Check our upcoming paper (T. Saito+14)!
1. The highest resolution (\(\sim 0''.1\)) Band 7 observation of VV114
   - to resolve gas around the AGN with \(\sim 40\) pc res.
   - required res. = NGC1068@cycle 0 (Garcia-Burillo+14).

2. Line imaging survey of VV114 using Band 3/4
   - to study what drives the molecular diversity in VV114.
   - \(\sim 40\) molecular lines will be detected (84 - 111/127 - 154 GHz).

3. \(R_{2-1/1-0}\) & \(R_{12/13}\) imaging toward NGC 1614 and NGC 3110
   - to understand the high ratio mechanisms in merging LIRGs.
   - CO(1-0), \(^{13}\)CO(1-0), CO(2-1), \(^{13}\)CO(2-1), CN, CS, CH\(_3\)OH ...
   - combined with SMA/CARMA/PdBI archive data

Thank you!