Active Galactic Nucleus and Extended Starbursts in a Midstage Merger VV 114

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Abstract

High-resolution (~0′′4) Atacama Large Millimeter/submillimeter Array (ALMA) Cycle 0 observations of HCO+ (4–3) and HCN (4–3) toward a midstage bright merger, VV 114, have revealed a compact nuclear (<200 pc) and extended (~3–4 kpc) dense gas distribution across the eastern part of the galaxy pair. We have found a significant enhancement of HCN (4–3) emission in an unresolved compact and broad (~290 km s⁻¹) component found in the eastern nucleus of VV 114, and suggest dense gas associated with the surrounding material around an Active Galactic Nucleus (AGN), with a mass upper limit of ~4 × 10⁶ M☉. The extended dense gas is distributed along a filamentary structure with resolved dense gas concentrations (~230 pc; ~10⁶ M☉) separated by a mean projected distance of ~600 pc, many of which are generally consistent with the location of star formation traced in Paα emission. Radiative-transfer calculations suggest moderately dense (n_H2 = 10⁵–10⁷ cm⁻³) gas averaged over the entire emission region. These new ALMA observations demonstrate the strength of the dense gas tracers for identifying both the AGN and the star-formation activity in a galaxy merger, even in the most dust-enshrouded environment in the local universe.

Key words: galaxies: evolution — galaxies: interactions — galaxies: starburst — telescopes

1. Introduction

Cosmological simulations have clearly established that galaxy collisions and mergers play major roles in the formation and evolution of galaxies by triggering a rapid mass build-up (e.g., Cole et al. 2000). High-resolution major merger simulations have shown that the star-formation physics is more dominated by mass fragmentation and turbulent motion across merging disks, forming massive clumps of dense gas clouds (M_gas = 10⁶–10⁹ M☉) and triggering star formation across the galaxy disks (Teyssier et al. 2010), or in a dense filamentary structure along the merging interface (Saitoh et al. 2009). In some cases, radial streaming can efficiently feed gas to the central black hole, possibly triggering an “AGN phase” during the course of the galaxy merger evolution (e.g., Hopkins et al. 2006).

An important observational test is to map dense gas tracers in merging ultra luminous infrared galaxies (ULIRGs), because they show a high degree of starburst activity, some of which harbor AGNs in their centers (Sanders & Mirabel 1996). The HCN (4–3) and HCO+ (4–3) emission, whose critical densities are n_{crit} ∼ 2 × 10⁴ cm⁻³ and n_{crit} ∼ 4 × 10⁵ cm⁻³ (Meijerink et al. 2007), respectively, are both reliable dense gas tracers, and now readily accessible at subarcsecond angular resolution with the advent of the Atacama Large Millimeter/submillimeter Array (ALMA). Here, we present ALMA Cycle 0 HCN (4–3) and HCO+ (4–3) observations of an IR-bright galaxy VV 114 with our primary goal to study the distribution of dense gas in the critical stage when the two gas-rich galaxies collide and merge.

VV 114 is a gas-rich (M_H2 = 5.1 × 10¹⁰ M☉; Yun et al. 1994; Iono et al. 2004; Wilson et al. 2008) interacting pair with high-infrared luminosity (L_IR = 4.0 × 10¹¹ L☉) located at D = 86 Mpc (1″ = 0.4 kpc). It consists of two optical galaxies (VV 114E and VV 114W) with a projected separation of 6 kpc (figure 1). Evidence for wide-spread star-formation activity and shocks across the entire system is found in the UV, optical, and mid-IR (Alonso-Herrero et al. 2002; Goldader et al. 2002; Rich et al. 2011). A dust-obscured AGN in VV 114E is also suggested by NIR spectroscopy (Le Floc’h et al. 2002) and X-ray observations (Grimes et al. 2006), suggesting that both starburst and AGN activities might have been triggered by the ongoing merger.
2. ALMA Observations

HCN (4–3) \((v_{\text{rest}} = 354.505\,\text{GHz})\) and HCO\(^+\) (4–3) \((v_{\text{rest}} = 356.734\,\text{GHz})\) observations toward VV 114 were obtained on 2012 June 1–3 in the Cycle 0 program of ALMA using the extended configuration. The digital correlator was configured with 0.488 MHz resolution for the spectral window that contained the emission lines. The absolute flux calibration was performed using Uranus, J1924−292 was used for bandpass calibration, and the time dependent gain calibration was performed using J0132−169 (6° away from VV 114). The total on-source time was 86 min.

We used the delivered calibrated data product and CLEANed the image down to 1.5 \(\sigma\) using the ALMA data reduction package, CASA. Channel maps with a velocity resolution of 30\,\text{km\,s}^{-1} were made, with a synthesized beam size of 0\:'5 × 0\:'4 (PA = 52°) (equivalent to 200 × 160 pc). The rms noise level was 0.9 mJy beam\(^{-1}\) for robust = 0.5 maps. The continuum was subtracted by using all of the line-free channels in the bandpass.

3. Distribution of HCN (4–3) and HCO\(^+\) (4–3)

HCN (4–3) and HCO\(^+\) (4–3) integrated-intensity maps are shown in figure 1. While the HCN (4–3) emission is only seen near the eastern nucleus of VV 114 and resolved into four peaks, the HCO\(^+\) (4–3) emission is more extended and has at least 10 peaks in the integrated-intensity map. The total integrated intensities of HCO\(^+\) (4–3) and HCN (4–3) are 15.3 ± 0.4 Jy km\,\text{s}^{-1} and 4.4 ± 0.2 Jy km\,\text{s}^{-1}, respectively. The higher HCO\(^+\) (4–3) flux observed with the Submillimeter Array (SMA) \((≥ 17\pm 2\,\text{mJy, Wilson et al. 2008})\) by using a 2\:'8 × 2\:'0 beam is likely attributed to missing flux by the ALMA observation. We show direct comparisons between the J = 4–3 (this work) and J = 1–0 [taken at the Nobeyama Millimeter Array (NMA), Imanishi et al. (2007)] transitions of both species in figure 2, after convolving the ALMA images with the NMA beam (7\:'5 × 5\:'5). While the J = 4–3 transitions of both species are concentrated near the near-infrared eastern nucleus with an extension to the west for HCO\(^+\) (4–3), the distributions of the HCN (1–0) and HCO\(^+\) (1–0) are different; the HCN (1–0) emission is separated into two clumps in the east–west direction, whereas the HCO\(^+\) (1–0) emission widely extends toward the western nucleus.

We label the six HCO\(^+\) (4–3) peaks in the eastern part of VV 114 as E0–E5 and the four detected in the western part of VV 114 as W0–W3 (figure 1, table 1). The HCO\(^+\) (4–3) and HCN (4–3) emission peaks are spatially consistent for E0–E3. The compact component E0 is unresolved with the current resolution, and the upper limit of size is <200 pc. HCN (4–3) emission is not detected in the overlap region (W0–W2), where both high CO (1–0) velocity dispersion and significant methanol detection suggest the presence of shocked gas (T. Saito et al. in preparation).

4. Dense Gas and AGN/Starburst Activity

4.1. Relative Strengths of HCN (4–3) and HCO\(^+\) (4–3) and a Signature of AGN

We present a comparison between the surface brightnesses of HCN (4–3) and HCO\(^+\) (4–3) in figure 3. Although the statistics are limited, the three molecular clumps (E1, E2, and E3) show an increasing trend between \(\Sigma_{\text{HCN}}\) and \(\Sigma_{\text{HCO}^+}\). In contrast, the ratio between the beam-averaged surface brightnesses of E0 is three times higher than those of E1, E2, and E3; E0 is the only component that has an HCN (4–3)/HCO\(^+\) (4–3) integrated flux ratio which is larger than unity [HCN (4–3)/HCO\(^+\) (4–3) = 1.6]. Gaussian
fits to the HCO$^+$ (4–3) and HCN (4–3) spectra at E0 give peak $= 9.0$ mJy and $\sigma = 123 \text{ km s}^{-1}$ [for HCN (4–3)], and peak $= 6.9$ mJy and $\sigma = 93 \text{ km s}^{-1}$ [for HCO$^+$ (4–3)]. Thus, the HCN (4–3) emission is not only brighter at E0 but also broader than the gas traced in HCO$^+$ (4–3), suggesting that the HCN (4–3) and HCO$^+$ (4–3) are tracing physically different gas at $< 200 \text{ pc}$ scales. Such a high relative intensity of the HCN emission is possibly a signature of a buried AGN, as suggested by previous studies (e.g., Kohno et al. 2001).

It has been known that the brightness of the HCN emission line is enhanced near the AGN compared to star-forming regions (Kohno et al. 2001), with a higher contrast in high $J$ transitions (Hsieh et al. 2012). Individual galaxies (e.g., NGC 1068; NGC 1097) have been studied extensively at high resolution (Kohno et al. 2003; Krips et al. 2011; Hsieh et al. 2012), clearly revealing the over abundance of HCN emission near the Seyfert nucleus, through $J = 1$ to 4. The exact cause of the enhanced intensity ratio is not clearly understood, and it could be due to gas excitation effects (e.g., density and temperature), the intensity of the incident radiation field (e.g., Photon-Dominated Region vs. X-ray-Dominated Region), IR pumping (e.g., García-Burillo et al. 2006), or other non-collisional excitation due to star formation or supernova explosions (see Krips et al. 2008 for a discussion). There is evidence showing a dominance of low-density ($< 10^{4.5} \text{ cm}^{-3}$) gas in a sample of AGNs (Krips et al. 2008), and hence the difference in the critical density is likely not the only reason for the difference in the relative abundance.

Regardless of the exact physical origin of the higher relative intensity of the HCN (4–3) emitting gas, the broad ($FWHM = 290 \text{ km s}^{-1}$) and compact ($< 200 \text{ pc}$) unresolved source E0 is of high interest, since it coincides with the region where past observations suggest the presence of a buried AGN.

We derived the upper limit to the dynamical mass by using $M_{\text{dyn}} = r \sigma^2 / G$ (assuming that the inclination is $90^\circ$ for the sake of simplicity), where $r$ is the radius enclosing the emission region, $\sigma$ the width of the HCN line, and $G$ the gravitational constant. The upper limit to the dynamical mass estimated from the line width and the beam size is $< 4 \times 10^8 M_\odot$. Since the HCN emission is generally believed to be optically thick, we estimated the dense gas mass of the E0 component by

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**Fig. 2.** Left: HCN (1–0) emission (in dark contours, Imanishi et al. 2007) compared with the HCN (4–3) emission convolved to the NMA resolution (in red contours). The contour levels for HCN (1–0) are the same as those of Imanishi et al. (2007), and the HCN (4–3) contours are $(2.8–4.8) \times 10^{-2}$ in steps of $0.2 \times 10^{-2}$ Jy beam km s$^{-1}$. The crosses indicate the locations of the near-infrared peaks shown in figure 2 of Imanishi et al. (2007). Right: Similar to the left panel but for the HCO$^+$ emission. The HCN (4–3) contours are $(1.0–1.7) \times 10^{-2}$ in steps of $0.1 \times 10^{-2}$ Jy beam km s$^{-1}$.

**Fig. 3.** Relation between the HCN (4–3) and HCO$^+$ (4–3) surface brightnesses for different regions in VV 114. The triangles represent upper limits to the HCN (4–3) surface brightness. The solid lines are the surface brightness ratios of 0.5, 1, and 2.
adopting the conversion factor provided in Gao and Solomon (2004). Using the integrated intensity of HCN (4–3) (see section 3) and HCN (1–0) = 7 Jy km s$^{-1}$ (Imanishi et al. 2007), we derived HCN (4–3)/(1–0) = 0.63. This yields a dense gas mass of $\sim 8.1 \times 10^8 M_\odot$, and hence > 2% of the total mass is in dense molecular form and a significant amount of dense gas is present in a very compact region.

Finally, we note that while these findings are evidence supporting a compact AGN near the eastern nucleus of VV 114, the 350 GHz/8.5 GHz flux ratio suggests the contrary. The ratio is 1.2 ± 0.1 for E0, and 1.1 ± 0.1 for E1 and E2, using an archival 8.5 GHz radio continuum image obtained from the VLA archive (beam size $\sim 0^\prime 9$) and a 350 GHz image obtained from the ALMA observation. The 350 GHz continuum emission is also unresolved at E0, but E1 and E2 show resolved structure. If the dominant source of the radio continuum emission is indeed due to hot plasma surrounding the AGN, then we expect this ratio to be higher near a putative AGN (i.e., E0), which is inconsistent with the current results and argues in favor of a common physical origin (e.g., a massive starburst) in all three regions. Higher resolution radio continuum imaging is necessary for understanding the origin of the radio emission in E0.

4.2. Extended Dense Gas Filament, Star Formation, and Global Gas Conditions

The average size of the clumps forming the filamentary structure (i.e., E1–E5, W0–W3) is 230 ± 70 pc, with an average dense gas mass of $\sim 10^8 M_\odot$ and a mean projected separation of $\sim 600$ pc. We compare the distribution of the HCO$^+$(4–3) and star-formation activity traced in Paα line in figure 4. A spatial correspondence between HCO$^+$(4–3) and the brightest peak of Paα is generally seen. Such a long filamentary dense gas structure and associated star-formation are predicted along the colliding interface of two colliding galaxies (Saitoh et al. 2009), and the masses are also consistent with the massive star-forming clumps predicted in simulations by Teyssier et al. (2010).

Finally, we derived the global physical conditions of gas by comparing the total integrated HCO$^+$(4–3)/(1–0) and HCN (4–3)/(1–0) ratios to the results from radiative transfer modeling (RADEX; Van der Tak et al. 2007). The results are $n_{H_2} = 10^5$–$10^6$ cm$^{-3}$ and T = 30–500 K, assuming abundance ratios of [HCO$^+$/[H$_2$] = 1.0 × 10$^{-9}$ (Irvine et al. 1987) and [HCN]/[HCO$^+$] = 0.1 to 1 (to be consistent with M82, Krips et al. 2008). Although the range of the derived temperature is too large to be meaningful, this constraint suggests the presence of moderately dense gas averaged over the entire galaxy pair. We caution here that these are average quantities that were derived without considering the difference in the spatial distribution between the $J = 4$–3 and 1–0 transitions (see figure 2). Higher angular-resolution imaging of the $J = 1$–0 transition is clearly needed in order to determine the spatial distribution of the physical properties.

5. Summary and Future Prospects

We present 0.4 resolution HCN (4–3) and HCO$^+$(4–3) observations toward a midstage IR bright merger, VV 114, obtained during the Cycle 0 program of ALMA. For the first time, these new high-quality maps enable us to investigate the central regions of this merging luminous infrared galaxy at 200 pc resolution. We find that both the HCN (4–3) and HCO$^+$(4–3) emission in the eastern nucleus of VV 114 are compact (< 200 pc) and broad [290 km s$^{-1}$ for HCN (4–3)] with high HCN (4–3)/HCO$^+$(4–3) ratio. From the new ALMA observations along with past X-ray and NIR observations, we suggest the presence of an obscured AGN in the eastern nucleus of VV 114. We also detect a 3–4 kpc long filament of dense gas, which is likely to be tracing the active star formation triggered by the ongoing merger. In a forthcoming paper, we will present a comprehensive modeling of VV 114 using our new $^{12}$CO (1–0), $^{13}$CO (1–0), and CO (3–2) ALMA observations, as well as a chemical analysis of the nucleus and the overlap region of VV 114 (Saito et al. in preparation).
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