RAINBOW Observations of Dense Molecular Gas in the Evolved Starburst Galaxy NGC 3628

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1. Abstract

The RAINBOW interferometer is a combined array between the Nobeyama Millimeter Array and the NRO 45 m telescope. This large collecting area of the RAINBOW enables us to perform sensitive observations with a short integrated time. We performed HCN, HCO^+, and 3 mm continuum observations toward the M82-like evolved starburst galaxy NGC 3628 with the RAINBOW and the NMA. The intensity ratio of HCO^+/HCN is about 1.3-1.8 in NGC 3628, which is similar to that of M82 (1.6). In this paper, we discuss a relationship between supernova explosions and HCO^+/HCN ratio.

2. Introduction

Observational studies of molecular gas in the Milky Way have shown that the strength of HCO^+ emission is often enhanced in shocked regions associated with young supernova remnants such as IC443 (e.g., Dickinson et al. 1980; Wooten 1981; Denoyer and Frerking 1981; Dickinson et al. 1992). One of the well known interpretation scheme is that the increase of cosmic ray (Rieu et al. 1992), which is emitted from supernova remnants, raises the cosmic ray ionization of the molecular hydrogen, which initiates production of HCO^+. Therefore, in evolved starburst galaxies which have a large numbers of supernova remnants, intensity of HCO^+ is expected to be enhanced by the effect of cosmic ray.

NGC 3628 is a nearby (D = 6.7 Mpc) edge-on starburst galaxy, and has a kpc scale soft X-ray outflow from the nuclear region (Fabbiano et al. 1990). The kpc scale outflow is suggested to originate from numerous supernova explosions, as in the case of the prototypical evolved starburst galaxy M82 (Rieke 1988; Rieke et al. 1988). NGC 3628 is therefore a good target to study the properties of molecular gas, i.e., the relationship between supernova explosions and HCO^+, in the late-phase starburst galaxies.

3. OBSERVATIONS

We performed aperture synthesis HCN, HCO^+, and 3 mm continuum observations simultaneously toward the nearby evolved starburst galaxy NGC 3628 using the Rainbow interferometer (RAINBOW) and the Nobeyama Millimeter Array (NMA) during March 2000 to February 2001. The all images were obtained using C, D, and RAINBOW configurations. The RAINBOW configuration is consisted of six 10 m antenna arrays in an AB configuration linked with the Nobeyama 45 m telescope. This large collecting area of the RAINBOW enables us to perform sensitive observations with a short integrated time. The front-ends are tunerless SIS receivers (Sunada et al. 1994). The receiver noise temperatures were about 30K (in double sideband), and the typical system noise temperatures (in single side band) were 300 - 800 K. As a back end, we used the Ultra Wide-Band Correlator UWBC (Okumura et al. 2000). The correlator was configured to cover 1024 MHz with 128 channels per baseline. The correlator enables us to perform simultaneous observations of HCN, HCO^+, and 3 mm continuum. The flux scales of 3C273 and 1116+128 were determined by comparisons with planets of known brightness temperature via NRAO 530. The uncertainty in the absolute flux scale is estimated to be $\sim \pm$ 10 %.

We made channel maps of HCN and HCO^+ emissions with a synthesized beam of 2.5 " $\times$ 2.0 " at velocity resolution 27 km s^{-1}. The typical noise levels of both maps are 2.5 mJy $beam^{-1}$. We also obtained 3 mm continuum with line free channels. The spatial resolution of 3 mm continuum map is 2.5" $\times$ 1.9". The noise level of the map is 0.35 mJy $beam^{-1}$.

4. Distribution of Dense Molecular Gas

We detected HCN and HCO^+ lines in channel maps with a velocity range of $V_{\rm LSR}$ = 613 - 1019 km s^{-1} and 677 - 1027 km s^{-1}, respectively. Figure 1 shows the total integrated intensity maps of HCN, HCO^+, 3 mm continuum, and CO emissions. The total intensity maps of HCN and HCO^+ show a concentration of dense molecular gas within the radius of 160 pc and a extended dense molecular gas ridge ($r <$ 330 pc). The extended component of dense molecular gas correspond to the CO disk (figure 1; Irwin, Sofue 1996). The distribution of the dense molecular gas is similar to those of 6 cm and 20 cm continuum emissions (Condon et al. 1982). We find a good spatial coincidence between dense molecular gas and 3 mm continuum emission (figure 1). Generally speaking, 3 mm continuum emission is dominated by free-free emission so that the strength of the 3 mm continuum directly relates with massive star formation rate like Hα emission in optical wavelength. Therefore this suggests that massive star formation occurs at the concentration, indicating an intimate physical link between gas density and massive star formation.

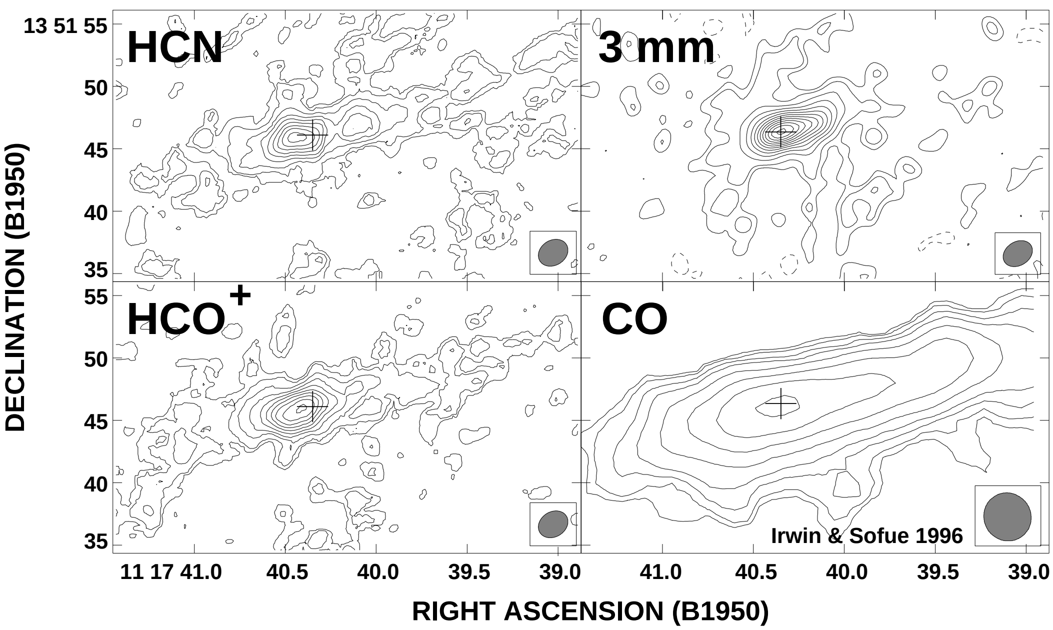

Figure 1: The observed integrated intensity maps in the central region of NGC 3628. The cross in each figure marks the field center and 20 cm radio continuum peak. Synthesized beams are shown at the bottom-right corner. The attenuation due to the primary beam pattern is not corrected in these maps. (HCN) Contour levels are 1, 2, 4, 6, 8, 10, 12, 14 and 16 σ, where 1 σ = 0.28 Jy $beam^{-1}$ km s^{-1}. (HCO^+) Contour levels are 1, 2, 4, 6, 8, 10, 12, 14 16 and 18 σ, where 1 σ = 0.27 Jy $beam^{-1}$ km s^{-1}. (3 mm continuum) Contour levels are -1, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 σ, where 1 σ = 0.35 mJy $beam^{-1}$. (CO) see Irwin and Sofue (1996).

Figure 2 contains the Position-Velocity diagrams of HCN and HCO^+ along the major axis (P.A. = 107°). A rigid rotating part is clearly seen in the both diagrams. This part is similar to that of CO (Irwin and Sofue 1996). The results suggests that a existence of "dense molecular gas disk" in the concentration of dense molecular gas (r < 5"). The overall kinematics components of HCO^+ is similar to that of HCN. A remarkable difference is visible between HCN and HCO^+ in the velocity structure of the rigid rotating part. The rigid rotating part of HCN has the maximum intensity other than the center, whereas HCO^+ peaks at the nucleus and the systemic velocity ($\simeq$ 843 km s^{-1}) . This difference of distributions in P-V diagrams means that the HCO^+/HCN ratio, $R_{\rm HCO^+/HCN}$, increases at nucleus. The $R_{\rm HCO^+/HCN}$ ratio at the nucleus is larger than that at the edge of the disk by a factor of 2 (nucleus: 1.3-1.8, edge of the disk: 0.7-0.9).

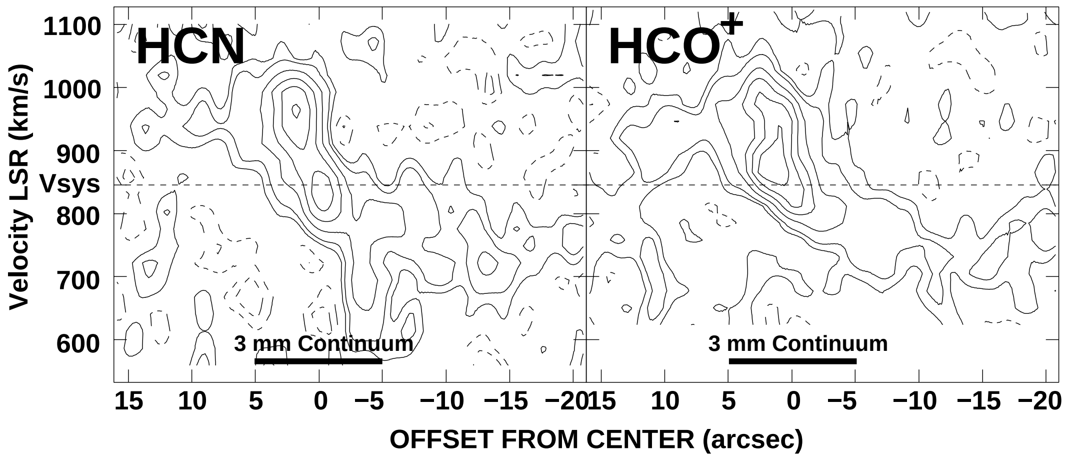

Figure 2: The position - velocity diagrams along major axis., Contours are at 2.5 × -2, -1, 1, 2, 4, 6, 8 and 10 mJy beam^{-1}. The horizontal bar indicates the distribution of the 3 mm continuum.

5. Properties of Molecular Gas

5.1. HCN to CO Intensity Ratio

Because HCN has a higher critical gas density ($n_{\rm H_2} > 10^4$ cm^{-3}) for collisional excitation than that of CO ($n_{\rm H_2} \sim 500$ cm^{-3}), HCN to CO integrated intensity ratio, $R_{\rm HCN/CO}$, is a measure of dense gas fraction to the total molecular gas within the observing beam (e.g., Kohno et al. 1999). The values of $R_{\rm HCN/CO}$ averaged within r < 64 pc and r < 128 pc are 0.06 ± 0.002 and 0.07 ± 0.002, respectivelty. These values are similar to those in "normal" galaxies such as the Galactic Center ($R_{\rm HCN/CO} \sim 0.08$; Paglione et al. 1998) and are significantly smaller than $R_{\rm HCN/CO}$ values in starburst galaxies such as NGC 253 (0.2 $\sim$ 0.3; e.g., Paglione et al. 1997, Sorai et al. 2000). These results indicate that the dense gas fraction in the central region of NGC 3628 is small compared with archtypical starburst galaxies such as NGC 253.

5.2. Consumption of Dense Gas

In the Milky Way Galaxy, it has been revealed that starformation occurs not in the diffuse envelopes of molecular clouds but in the dense part, i.e., dense molecular cores (Lada 1992). This means that dense molecular gas is the essential fuel of starburst phenomena. In fact, good spatial coincidence between HCN and Hα emission has been reported in nearby starburst galaxies (e.g. Paglione et al. 1998; Kohno et al. 1999). But, although many authers report that NGC 3628 is in a phase of ongoing starburst (e.g., Zhao et al 1997), the $R_{\rm HCN/CO} \sim 0.07$ of NGC 3628 suggests that the dense gas fraction of NGC 3628 is close to those of normal galaxies. Why is the fraction of dense gas of NGC 3628 small compared with archtypical starburst galaxies? Since the kpc scale outflow (Fabbiano et al. 1990) of NGC 3628 is suggested to originate from numerous supernova explosions, as in the case of the prototypical evolved starburst galaxy M82 (Rieke et al. 1988, Rieke 1988), it is considered that long-term star formation has occurred in the central region of NGC 3628, and that NGC 3628 may be now in a evolved phase of starburst. Because long-term star formation consume a large amount of dense molecular gas, the small fraction of dense gas, may indicates a consumption of the dense gas, which is caused by starburst.

5.3. Meaning of $R_{\rm HCO^+/HCN}$

HCO^+ may trace cosmic-ray-dominated dense molecular gas, since the production of HCO^+ is initiated by the cosmic ray ionization of molecular hydrogen. On the other hand, since HCN has a similar critical gas density for collisional excitation as HCO^+ but it is less sensitive to the presence of cosmic ray, $R_{HCO^+/HCN}$ could be a tracer of ionizing cosmic ray within dense molecular clouds (Rieu et al. 1992). Thus, the enhanced $R_{HCO^+/HCN}$ in the nucleus of NGC 3628 suggests that there is a large amount of ionizing cosmic ray in the dense molecular gas disk in this galaxy. Previous observations at radio wavelengths report that there are numerous supernova remnants in the central region (e.g., Cole et al. 1998). Considering these results, we suggest that the presence of numerous supernova remnants in the nucleus of NGC 3628 is responsible for the observed enhancement of the $R_{HCO^+/HCN}$, and that the enhanced HCO^+/HCN ratio may be an indicator of evolved starburst regions.

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