ARCLIKE DISTRIBUTION OF HIGH CO ($J = 3–2$)/CO ($J = 1–0$) RATIO GAS SURROUNDING THE CENTRAL STAR CLUSTER OF THE SUPERGIANT H II REGION NGC 604

T. Tosaki, R. Miura, T. Sawada, N. Kuno, K. Nakanishi, K. Kohno, S. K. Okumura, and R. Kawabe

Received 2007 April 13; accepted 2007 June 4; published 2007 July 9

ABSTRACT

We report the discovery of a high CO ($J = 3–2$)/CO ($J = 1–0$) ratio gas with an arclike distribution ("high-ratio gas arc") surrounding the central star cluster of the supergiant H II region NGC 604 in the nearby spiral galaxy M33, based on multi-$J$ CO observations of a 5' × 5' region of NGC 604 conducted using the ASTE 10 m and NRO 45 m telescopes. The discovered "high-ratio gas arc" extends to the southeast-northwest direction with a size of ~200 pc. The western part of the high-ratio gas arc closely coincides with the shells of the H II regions traced by Hα and radio continuum peaks. The CO ($J = 3–2$)/CO ($J = 1–0$) ratio, $R_{3–2/1–0}$, ranges between 0.3 and 1.2 in the observed region, and the $R_{3–2/1–0}$ values of the high-ratio gas arc are around or higher than unity, indicating very warm (Tkin ≥ 60 K) and dense (nH ≥ 10$^{4}$–10$^{5}$ cm$^{-3}$) conditions of the high-ratio gas arc. We suggest that the dense gas formation and second-generation star formation occur in the surrounding gas compressed by the stellar wind and/or supernova of the first-generation stars of NGC 604, i.e., the central star cluster of NGC 604.

Subject headings: galaxies: individual (M33) — H II regions — ISM: individual (NGC 604) — ISM: molecules — stars: formation

1. INTRODUCTION

GIANT or supergiant H II regions (hereafter referred to as GHRs) are one of the most prominent objects in star-forming galaxies at the optical wavelength. Their sizes often reach a scale of a few 100 pc, and their Hα luminosities are typically of the order of a few 10$^{6}$–10$^{7}$ ergs s$^{-1}$, which corresponds to a few 10 to a few 100 O5 stars (Kennicutt 1984). The structure of GHRs is characterized by (1) the presence of a central young star cluster and (2) extended shells and/or arclike filaments surrounding the central star cluster. For example, 30 Dor in the Large Magellanic Cloud (LMC), which is the most luminous H II region in the Local group, houses the compact cluster R136, which is classified as a super star cluster (SSC; Hunter et al. 1995). On the other hand, NGC 604 resides in M33, which is the second-most luminous supergiant H II region after 30 Dor and hosts a scaled OB association (Hunter et al. 1996; Maiz-Apellániz et al. 2004). These central star clusters appear to have formed during the initial stages of the formation of GHRs and are expected to have a strong impact on their natal molecular clouds due to their strong UV radiation, stellar wind, and supernova explosion. Therefore, GHRs provide us with an ideal environment to understand the clustered OB star formation process and their impact on the ambient interstellar medium (ISM). These physical processes are also crucial in the evolution of starburst in galaxies.

In this study, we present the 12CO ($J = 3–2$) and 13CO ($J = 1–0$) observations of NGC 604 in the nearest face-on spiral galaxy M33 using the Atacama Submillimeter Telescope Experiment (ASTE) 10 m and the Nobeyama Radio Observatory (NRO) 45 m telescopes (see Fig. 1). The structure of NGC 604 is complicated, containing many shells, filaments, and arclike structures; furthermore, there is a central star cluster surrounded by arclike H II regions (Gómez de Castro et al. 2000) and ~200 massive OB stars (González Delgado & Pérez 2000). Several radio components exist in the arclike H II regions, which are photoionized from the inside by the obscured massive stars, embedded in the further extended halo (Churchwell & Goss 1999). The atomic and continuum emission of NGC 604 in the far-infrared wavelengths is also bright (Higdon et al. 2003; Hippelein et al. 2003). Its proximity ($D = 0.84$ Mpc; Freedman et al. 1991) and the favorable inclination angle of the host galaxy ($i = 52^\circ$; Corbelli & Salucci 2000) allow us to clarify the detailed distributions of young stars and the associated molecular clouds within this extreme star-forming region.

Our objectives in conducting these molecular line observations are (1) to investigate the spatial variation of the physical properties of molecular gas and (2) to understand their relationship with the GHR formation processes. Several researchers have previously reported on observations of M33 in CO ($J = 1–0$) emission, which can be collisionally excited even in low-density molecular gases such as $n(H_2) \sim 10^2$ cm$^{-2}$, and a large molecular cloud complex associated with NGC 604 has been detected (Wilson & Scoville 1992; Viallefond et al. 1992; Engargiola et al. 2003; Heyer et al. 2004). Wilson et al. (1997) observed 12CO ($J = 2–1$), 13CO ($J = 2–1$), and 12CO ($J = 3–2$) emission lines, probing the denser components of molecular gas [$n(H_2) > 10^4$–10$^5$ cm$^{-3}$], toward two points in the NGC 604 region; they found that the kinetic temperatures of the molecular clouds associated with the H II regions were systematically higher than those not associated with the H II regions. Nevertheless, no map has been created for these high-J CO lines thus far, and therefore the spatial variation of the physical conditions of the molecular clouds and their relationship with the central star cluster and the surrounding Hα shells/ arclike structures have not yet been well understood.

Our new observations conducted using the ASTE 10 m and NRO 45 m telescopes provide high-sensitivity 12CO ($J = 3–2$) and 13CO ($J = 1–0$) images of a 5' × 5' or 1.3 × 1.3 kpc region located in the center of NGC 604 with an effective spatial resolution of 25'' or 100 pc. Using these new images, we report the discovery of a high CO ($J = 3–2$)/CO ($J = 1–0$) ratio gas with
an arclike distribution (high-ratio gas arc) surrounding the central star cluster of NGC 604.

2. OBSERVATIONS

We conducted $^{12}$CO ($J = 3–2$) observations using the ASTE 10 m submillimeter telescope located in the Atacama desert, Chile (Ezawa et al. 2004) from 2006 July to August. This was a part of our ADloS project, which is an extragalactic CO ($J = 3–2$) imaging survey to obtain a global view of the dense molecular medium in galaxies (Kohno et al. 2007). We also conducted $^{13}$CO ($J = 1–0$) observations from 2005 December to 2006 March using the NRO 45 m telescope equipped with a 5 × 5 pixel focal-plane SIS array receiver (BEARS) capable of simultaneously observing 25 positions in the sky (Sunada et al. 2000). Further information on the 45 m observations will be reported in detail in a forthcoming paper (R. Miura et al. 2007, in preparation).

The front end for the ASTE observations was a single-pixel cartridge-type 350 GHz SIS receiver (SC 345; Kohno 2005). An XF-type digital spectrometer was used to cover a velocity width of 445 km s$^{-1}$ with a velocity resolution of 5 km s$^{-1}$ at 345 GHz. The observations were conducted remotely from the ASTE operation rooms in National Astronomical Observatory of Japan (NAOJ) Mitaka and NRO, Japan, using the N-COSMOS3 network observation system developed by NAOJ (Kamazaki et al. 2005). The typical system temperature in double sideband (DSB) was 200 K. The absolute pointing accuracy and main beam efficiency were verified by observing the CO ($J = 3–2$) emission of o-Cet at intervals of every 2 hr. They were better than 2$''$ rms and 0.6% during the observation runs, respectively. The stability of efficiency was also monitored using o-Cet and was found to be stable within ±10%.

The on-the-fly mapping technique was employed to obtain the $^{12}$CO ($J = 3–2$) and $^{13}$CO ($J = 1–0$) data. The “scanning noise” was removed by combining the scan using the PLAIT algorithm described by Emerson & Graeve (1988).

The full width at half-power (FWHP) beams for the ASTE 10 m and NRO 45 m observations were 22$''$ and 16$''$ at the rest frequencies of $^{12}$CO ($J = 3–2$) (345 GHz) and $^{13}$CO ($J = 1–0$) (115 GHz), respectively. We convolved these maps to a common spatial resolution of 25$''$; this enabled us to measure CO ratios directly.

3. RESULTS

Figure 2 shows the velocity-integrated total intensity maps of $^{12}$CO ($J = 1–0$) and $^{13}$CO ($J = 3–2$) emissions, integrated over a velocity width of 200 km s$^{-1}$ (from $V_{\text{LSR}} = -350$ to $-150$ km s$^{-1}$). Although this velocity range was larger than that of the emission, $\sim 80$ km s$^{-1}$, this has no effect on the total integrated intensity due to the baseline subtraction.

Wide-spread CO ($J = 1–0$) emission can be seen within the mapped region. They are distributed around NGC 604, on the arm to its north, and on the downstream side of the arm. The typical size of the clumps in the map is $\sim 100$ pc, and they aggregate to a larger complex that is similar to Giant Molecular Associations (GMAs; Rand & Kulkarni 1990). On applying the CLFIND method (Williams et al. 1994) to the CO ($J = 1–0$) data 10 clumps were detected in this region and a few of them were new detections not reported in previous CO ($J = 1–0$) observations. Detailed properties of these CO clumps will be reported in a forthcoming paper (R. Miura et al. 2007, in preparation).

On the other hand, the $^{12}$CO ($J = 3–2$) map exhibits a compact morphology; the major CO ($J = 3–2$) emission is confined to a small area close to the central cluster of NGC 604. Furthermore, the strong $^{12}$CO ($J = 3–2$) peaks are located to the north of the $^{12}$CO ($J = 1–0$) complex, i.e., the vicinity of the central star cluster of NGC 604. Interestingly, no clear CO
In this subsection, we discuss the relationship among the high-ratio gas arc, the central star cluster, and the embedded young stars accompanying the Hα shell.

The observational results obtained in this study can be explained by the following scenario. First, stars were formed in the northern part of GMA; this is referred to as “first-generation star formation.” These stars can now be observed as the central star cluster. Next, their stellar wind and supernova compressed the surrounding ISM. As a result, a dense gas layer was formed around the central star cluster. This is observed as the arclike distribution of the high ratio gas. New stars were then formed within the dense gas layer; this is referred to as “second-generation star formation.” These stars can now be observed as the central star cluster. These secondary young stars formed in the dense gas layer can now be observed as the Hα shells and compact radio continuum sources as seen in Figure 3. Figure 4 summarizes the schematic view of the proposed

4.2. Triggered Dense Gas and Star Formation by “First-Generation” Star Formation

In this subsection, we discuss the arclike distribution of the high-ratio gas arc, suggesting that massive stars are formed within the warm and dense gas layers depicted as the high-ratio gas arc. Here it should be noted that the high $R_{3-2/1-0}$ values in the arc are due to not only the high kinetic temperature but also the high gas density. If the high $R_{3-2/1-0}$ values are attributable solely to the UV heating from these newly formed stars, the high line ratio can only coincide with the Hα shells, i.e., the high-ratio gas should be observed predominantly in the western part of Figure 3. However, our line ratio map indicates the presence of high-ratio gas, even in the eastern part of the molecular clouds, which is set apart from the bright Hα shell seen in Figure 3 (right panel). Furthermore, another calculation conducted using a photodissociation region (PDR) supports that the high $R_{3-2/1-0}$ values could be attributable to the high gas density (Kaufman et al. 1999).

In conclusion, we suggest that the high-ratio gas arc reveals the presence of warm and dense molecular gas layers, and the massive stars now form within the dense gas arc.

4. DISCUSSION

4.1. Nature of High-Ratio Gas Arc

In this subsection, we discuss the physical conditions of the discovered high-ratio gas arc. A model calculation using large velocity gradient approximation suggests that the high ratio gas ($R_{3-2/1-0} \sim 1$) requires a kinetic temperature of $T_{\text{kin}} > 60$ K and a gas density of $n(H_2) \sim 10^3$–$10^4$ cm$^{-3}$ (Muraoka et al. 2007, Fig. 9). These values are in very good agreement with the results of Wilson et al. (1997) for the cloud NGC 604-2. These indicate that the warm and dense gases are distributed around the central star cluster with an arclike morphology.

In addition, there exists an arclike distribution of Hα emission (Gómez de Castro et al. 2000), wherein several compact H II regions are embedded, as revealed by radio continuum observations (Churchwell & Goss 1999). These distributions exhibit a striking similarity to the western part of the high-ratio gas arc, suggesting that massive stars are formed within the warm and dense gas layers depicted as the high-ratio gas arc.

FIG. 3.—Maps of the ratio of $^{12}$CO ($J = 3–2$) to $^{12}$CO ($J = 1–0$) (left) and the Hα emission by HST (right; from the HST archive). The contour levels are 0.4, 0.6, 0.8, and 1.0. The crosshairs in the center indicates the position of the central star cluster of NGC 604, while the stars represent the peak positions of the H II regions detected by λ3.6 cm radio continuum emission (Churchwell & Goss 1999). These maps clearly reveal the presence of high ratio gas with an arclike morphology surrounding the central star cluster of NGC 604.

FIG. 4.—Schematic view of NGC 604.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Schematic view of NGC 604.}
\end{figure}
scenario for NGC 604. A similar situation is also reported in the N11 region, which is the second largest star-forming region of LMC (Hatano et al. 2006).

Certain observations provide supporting evidence for the proposed scenario. First, the velocity field derived from the Hα emission of NGC 604 indicates that it consists of many filaments formed by multiple blowout events due to the energy injected by massive stars (Tenorio-Tagle et al. 2000). No Hα emission or CO emission peaks are seen in the central star cluster; however, the arclike structure of the high R a/21-α ratio gas has been associated with both Hα and CO emissions. These facts suggest that the H II regions embedded in the high-ratio gas arc are in fact ongoing star-forming regions, while the central star cluster that has already dispersed ISM is the "past" star-forming region.

Second, the presence of shocks in the Hα shell was observed by optical spectroscopy (Gómez de Castro et al. 2000); these are attributed to the detected expanding motion (Tenorio-Tagle et al. 2000). This could be consistent with the view that the ISM surrounding the central star cluster was compressed by its energy blowout. The observation of a compact H II hole suggests the presence of SNR in NGC 604 (Deul & den Hartog 1990); further, the observation of X-ray–emitting hot plasma (Misanovic et al. 2006) may also support such expanding motion.

Further evidence is provided by the optical narrowband imaging of [S II] and [O III] emissions (Tenorio-Tagle et al. 2000). In the arclike region with the high ratio, the [O III]/Hα ratio is high while the [S II]/Hα ratio is relatively low. Because both high [O III]/Hα and low [S II]/Hα ratios correspond to a high excitation condition, it is suggested that the stars in the high-ratio gas arc region are significantly younger than those in other regions. This difference between the stellar ages of the central star cluster and the surrounding young stars is consistent with the proposed scenario.

On the other hand, the age of the central cluster of NGC 604 has been estimated to be ~3 × 10^6 yr (Bruhweiler et al. 2003; González Delgado & Pérez 2000). Therefore, the timescale required to expand to the size of the detected H II region, as indicated by the radio continuum observations, would be in the range of 10^6 to 8 × 10^6 yr (Churchwell & Goss 1999). We found no significant difference between the central star cluster ages and the radio-derived ages.

However, it should be noted that the stellar age was estimated over the region including both the high-ratio gas arc region and the central star cluster, i.e., the derived stellar age is a mixture of the proposed second-generation stars (in the Hα shell) and the first-generation ones (i.e., the central cluster). Consequently, inconsistency between these timescales and the proposed scenario is therefore not decisive, and we need to conduct further observations to obtain spatially resolved stellar age measurements across the NGC 604 region.

Note that the compressed warm dense gas is seen only in the southern and western parts of the star cluster. It is due to the direction from which material flows, namely, from the southwest to the northeast in spiral arm, and expanding material from first generation stars meets material flowing from the southwest into the arm. This suggests that a shock moves from the northeast to the southwest.

Thus, we conclude that the arclike structure of the high-ratio gas is the site of second-generation star formation triggered by first-generation star formation. NGC 604 is an example of a large-scale sequential star formation.

We thank the referee C. Wilson, whose invaluable comments improved our Letter. We would like to thank the staff of the Nobeyama Radio Observatory and the ASTE team for their kind support in conducting our observations. This study was financially supported by the MEXT Grant-in-Aid for Scientific Research on Priority Areas No. 15071202. The Nobeyama Radio Observatory is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences (NINS). We would also like to thank Dr. Shingo Nishiura for providing us with the optical image of M33 acquired using the 1.05 m Schmidt telescope installed at the KISO observatory, operated by the Institute of Astronomy, University of Tokyo.

Facilities: ASTE, NRO 45 m telescope (BEARS).