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THE GALACTIC-SCALE MOLECULAR OUTFLOWS IN STARBURST GALAXIES NGC 2146 AND NGC 3628

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ABSTRACT

Starburst galaxies have strong star formation activity and generate large scale outflows which eject a huge amount of gas mass. This process affects galaxy activity, and therefore, the detailed study of nearby starburst galaxies could provide valuable information for the study of distant ones. So far there have been only a few studies of galactic-scale molecular outflows due to the sensitivity limitation of telescopes. Our study provides two nearby examples, NGC 2146 and NGC 3628. We used Nobeyama Millimeter Array (NMA) CO(1-0) data, Chandra soft X-ray data, and NMA 3 mm data to study the kinematics of molecular outflows, their interaction with ionized outflows, and the star forming activity in the starburst region. We found that the gas ejected through molecular outflows is much more significant than that used to form stars.

Key words: journals: individual: PKAS — galaxies: starburst — ISM: jets and outflows

1. INTRODUCTION

Starburst galaxies are currently undergoing intense star formation in their central region. Their strong star formation produces galactic-scale outflows and ejects large amounts of molecular gas. This consumption of molecular gas affects the star forming activity in galaxies. Starburst galaxies are good candidates for studying molecular gas consumption in galaxies because of their strong activity. So far there are three techniques to detect molecular outflows and superbubbles, which are the early stage of outflows: (1) High-velocity CO wings (Alatalo et al., 2011; Chung et al., 2011), (2) P-cygni profiles (Sakamoto et al., 2009) and (3) Direct imaging (Nakai et al., 1987; Matsushita et al., 2000, 2005). The accurate measurement of outflowing molecular gas relies on the third method. However, measurments of the third sort are rare because it is difficult to directly observe molecular outflows due to their diffuse/extended nature and inadequate instrumental sensitivities. Our studies provide observations of two starburst galaxies, NGC 2146 and NGC 3628.

NGC 2146 is a nearby (17.2 Mpc, $1'' = 80$ pc; Tully 1988), IR luminous ($\log L_{\rm IR}/L_\odot = 11.07$; Sanders et al. 2003), edge-on ($i = 63°$; Della Ceca et al. 1999) starburst galaxy. Soft X-ray images show kpc-scale outflows from the starburst region around the galactic center (Inui et al., 2005; Della Ceca et al., 1999; Armus et al., 1995). So far, there is no clear evidence of molecular bubbles or outflows in NGC 2146 due the lack of prior deep observations.

NGC 3628 is a nearby (D = 7.7 Mpc; $1'' = 37$ pc Tully 1988), edge-on ($i = 87°$ Tully 1988), and IR luminous ($\log L_{\rm IR}/L_\odot = 10.25$; Sanders et al. 2003) galaxy. Chandra X-ray Observatory (CXO) images (Strickland et al., 2001, 2005) show that NGC 3628 has an asymmetric plasma bipolar outflow at $\sim$ 7–10 kpc scale. Irwin & Sofue (1996) claimed that their CO(1-0) Nobeyama Millimeter Array (NMA) observations detected four expanding molecular superbubbles. However, no molecular outflow has been detected.

The characteristics of these two starburst galaxies are very similar to the prototypical starburst galaxy M82, which has hundred parsec scale superbubbles and kiloparsec scale outflows. Thus, it is natural to expect that we could detect molecular outflows in NGC 2146 and NGC 3628.

2. OBSERVATIONS AND ARCHIVAL DATA

2.1. NMA CO(1-0) Observations

We performed deep CO(1-0) observations toward the central $1' - 2'$ region of the edge-on starburst galaxies NGC 2146 and NGC 3628 with the Nobeyama Millimeter Array (NMA), which consists of six 10-meter antennas located at the Nobeyama Radio Observatory (NRO). The total on-source integration time for NGC 2146 was $\sim$44 hours, with a phase tracking center of R.A.(J2000) = $06^{\rm h}18^{\rm m}37.6^{\rm s}$ and Dec.(J2000) = $78°21'24.1''$. The total on-source integration time for NGC 2146 was $\sim$44 hours, with a phase tracking center of R.A.(J2000) = $11^{\rm h}20^{\rm m}17^{\rm s}$ and Dec.(J2000) = $13°35'20''$.

2.2. Chandra X-ray Archival Data

The soft X-ray data of NGC 2146 was obtained by collaborators (Inui et al., 2005). The data were taken with the Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-ray Observatory (CXO). The center position of NGC 2146 is R.A.(J2000) = $06^h18^m38.4^s$ and Dec. (J2000) = $78°21'28.2''$, with a total exposure time of 60 ks. The NGC 3628 X-ray data is from the CXO archive (Strickland et al., 2001, 2005), with a center position of NGC 3628 of R.A. (J2000) = $11^h20^m04.9^s$ and Dec. (J2000) = $13°30'50.5''$ and a total exposure time of 60 ks.

2.3. NMA 3 mm Observations

We have used NMA to observed 3 mm continuum emission in the central $\sim 30'$ region of the starburst galaxies NGC 2146 and NGC 3628. The phase tracking centers of both galaxies are the same as those of the NMA CO(1-0) observations. The total on-source time for NGC 2146 is ~31 hours, and that for NGC 3628 is ~20 hours.

3. RESULTS AND DISCUSSION

3.1. The Properties and Kinetics of Molecular Outflows and Superbubbles

The CO(1-0) data traces the molecular gas. Figure 1 and Figure 2 show the integrated intensity map and the velocity map of two starburst galaxies, NGC 2146 and NGC 3628, respectively. The properties of the molecular outflows and superbubbles in the two starburst galaxies are listed in Table 1. In both galaxies, we first detected 350–2000 pc scale molecular superbubbles or outflows with expanding velocities of 40–200 km s^{-1}. The kinetic energy of the molecular superbubbles or outflows is $\sim 10^{54-55}$ erg, which corresponds to tens of thousands of supernova explosions. The mass of the molecular superbubbles or outflows is $\sim 10^{7-8}$ $M_\odot$, which corresponds to 1–10% of the total molecular gas in each galaxy. The expanding timescale is $\sim 10^{6-7}$ yr. Therefore, the mass loss rate through molecular superbubbles or outflows is 4–34 $M_\odot$ yr^{-1}.

3.2. The Mechanism to Push Molecular Outflows

The soft X-ray data traces the hot ionized gas. In Figure 3, we overlap the CO(1-0) (cyan contours), soft X-ray (color scale), and 3 mm data (white contours) in one image to compare the distribution of molecular gas, ionized gas, and the starburst region. In NGC 2146 OF1, the ionized gas is embedded in the molecular gas, and a similar structure appears in SB1 with weaker emission. In NGC 3628, ionized gas and molecular gas are located in similar regions.

In order to determine the mechanism driving the molecular outflows, we compared the ram pressure of the ionized gas on the molecular outflow, and the thermal pressure of the ionized outflow. Table 2 lists the ram pressure and the thermal pressure in the two starburst galaxies. The results show that the ram pressure is several orders higher than the thermal pressure. This indicates that the mechanism driving the molecular outflows is primarily the shock of the supernova explosions rather than the thermal expansion of hot gas.

3.3. The Star Forming Activities in Starburst Region

The NMA 3 mm data trace the radio free-free continuum emission, and consequently the new born massive stars. In Figure 3, the white contours represent the distribution of new massive stars, called the starburst region. We can describe the activity in the starburst region from our 3 mm data: the flux density around 3 mm is dominated by thermal free-free emission, but part of the emission is contributed by non-thermal synchrotron radiation. After excluding the contamination from non-thermal synchrotron radiation (Condon, 1992), we can estimate the production rate of Lyman continuum photons from massive stars (Condon, 1992). Thus, the Star Formation Rate (SFR) can be derived by assuming the mass distribution follows a Salpeter IMF (Kennicutt, 1998). In NGC 2146, the SFR in the starburst region is 15.7 $M_\odot$ yr^{-1}. In NGC 3628, the SFR in the starburst region is 2.1 $M_\odot$ yr^{-1}.

3.4. The Significance of Molecular Outflows

In order to determine whether molecular outflows and/or superbubbles significantly consume the molecular gas in starburst galaxies, we compare the two major processes of molecular gas consumption: (1) SFR in the starburst region, and (2) mass loss rate through molecular outflows and superbubbles. The results are listed in Table 3. We found that the mass loss rate is ~2–5 times higher than the SFR. This indicates that the loss of molecular gas through outflows and superbubbles is more significant that that consumed by the formation of stars.

4. CONCLUSIONS

We first provide a detailed study of molecular superbubbles and outflows in two edge-on starburst galaxies, NGC 2146 and NGC 3628. From our NMA CO(1-0) observation data, the CXO soft X-ray archival data, and the NMA 3 mm free-free emission data, we have three conclusions: (I) The sub-kpc to kpc scale molecular superbubbles and outflows have expanding velocities of 40–200 km s^{-1} and energies of $\sim 10^{54-55}$ erg. (II) The mechanism driving the molecular outflows is primarily the shocks from supernova explosions. (III) The mass loss rate through molecular superbubbles and outflows is much higher than the SFR. This indicates that the molecular outflows dominate the gas consumption in starburst galaxies.

REFERENCES

Alatalo, K., Blitz, L., & Young, L. M., et al., 2011, Discovery of an Active Galactic Nucleus Driven Molecular Outflow in the Local Early-type Galaxy NGC 1266, ApJ, 735, 88

Armus, L., Heckman, T. M., Weaver, K. A., & Lehnert, M. D., 1995, ROSAT Observations of NGC 2146: Evidence for a Starburst-driven Superwind, ApJ, 445, 666

Table 1
THE PROPERTIES OF THE MOLECULAR OUTFLOWS AND SUPERBUBBLES

		Size (pc)	$v_{\rm expanding}$ (km s^{-1})	$t_{\rm expanding}$ (Myr)	M ($10^8 M_\odot$)	$E_{\rm kinetic}$ (10^{54} erg)	dM/dt * ($M_\odot$ yr^{-1})	Ref.
NGC 2146	OF1	2000	0–200	10–20	3.4	30	17–24	†
	SB1	800–1200	40–60	13–29	2.6	4–9	9–20	†
NGC 3628	OF	350–500	80–100	3–7	0.3	2–3	4–10	‡

* The mass loss rate through molecular outflows or superbubbles.
† Tsai et al. (2009). ‡ Tsai et al. (2012).

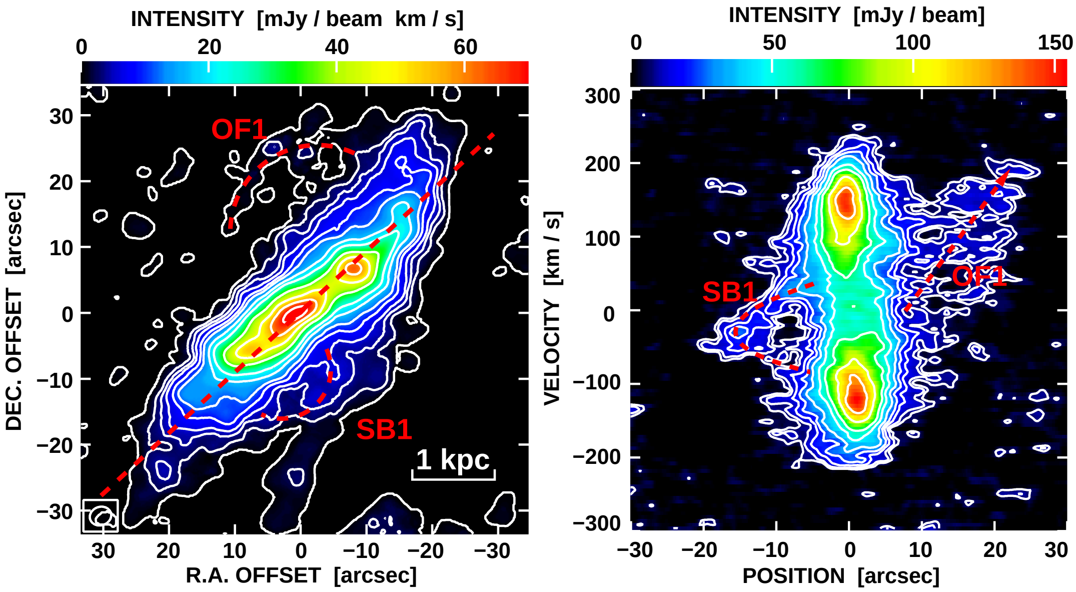

Figure 1. The NMA CO(1-0) data of NGC 2146 (Tsai et al., 2009). (Left panel) Integrated Intensity Map (moment 0). The synthesized beam size is $3.4'' \times 2.8''$ (280 pc × 230 pc). The red-dotted line indicates the galactic disk. The red-dotted arcs indicate the superbubble (SB1) and outflow (OF1). (Right panel) The position-velocity (p–v) diagram along the minor axis. The red-dotted arc indicates the velocity of SB1. The red-dotted line indicates the velocity gradient of OF1.

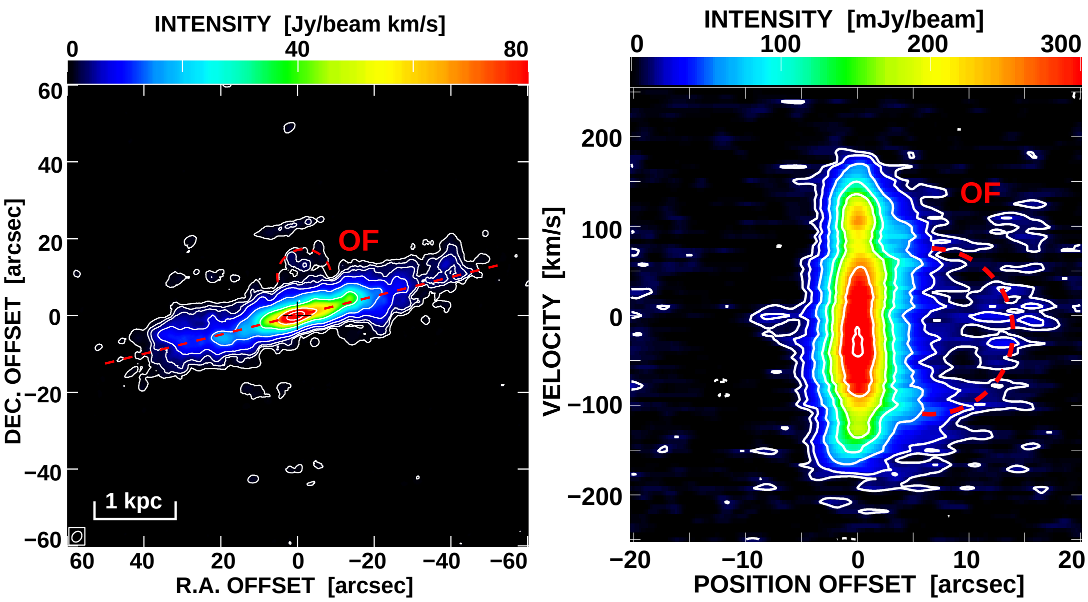

Figure 2. The NMA CO(1-0) data of NGC 3628 (Tsai et al., 2012). (Left panel) Integrated Intensity Map (moment 0). The synthesized beam size is $3.0'' \times 2.4''$ (112 pc×88 pc). The red-dotted arc indicates the outflow (OF). (Right panel) The p–v diagram along the minor axis of NGC 3628. The red-dotted arc indicates the velocity of outflow (OF).

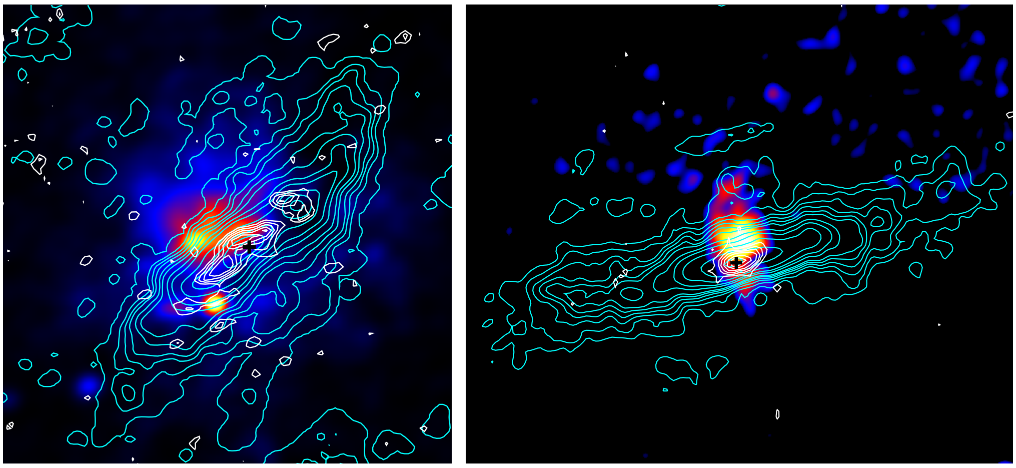

Figure 3. The overlap images of the NMA CO(1-0) data (cyan contour), the CXO soft X-ray data (color), and the NMA 3 mm data (white contour) of NGC 2146 (Left panel) and NGC 3628 (Right panel). The synthesized beam size of NMA CO(1-0) data and that of NMA 3 mm data are the same. The black cross is the dynamical center of CO(1-0) data.

Table 2
THE PRESSURE BETWEEN MOLECULAR OUTFLOWS AND IONIZED OUTFLOWS

		$P_{\rm ram}$ (dyn cm^{-2})	$P_{\rm thermal}$ (dyn cm^{-2})	Ref.
NGC 2146	OF1	$10^{-(7-8)}$	$10^{-(11-13)}$	†
NGC 3628	OF	$10^{-(7-8)}$	$10^{-(11-13)}$	‡

† Tsai et al. (2009). ‡ Tsai et al. (2012).

Table 3
THE MASS LOSS RATE VS. STAR FORMATION RATE

		dM/dt * ($M_\odot$ yr^{-1})	SFR # ($M_\odot$ yr^{-1})
NGC 2146	OF1 + SB1	26–44	15.7
NGC 3628	OF	4–10	2.1

* The mass loss rate through molecular outflows and superbubbles.
# The star formation rate in starburst region.

Chung, A., Yun, M. S., & Naraynan, G., et al., 2011, Evidence for 1000 km s-1 Molecular Outflows in the Local ULIRG Population, ApJL, 732, 15

Condon, J. J., Condon, M. A., Gisler, G., & Puschell, J. J., 1982, Strong Radio Sources in Bright Spiral Galaxies. II - Rapid Star Formation and Galaxy-galaxy Interaction, ApJ, 252, 102

Condon, J. J., 1992, Radio Emission from Normal Galaxies, ARA&A, 30, 575

Della Ceca, R., Griffiths, R. E., & Heckman, T. M., et al., 1999, ASCA Observations of the Starburst-driven Superwind Galaxy NGC 2146: Broadband (0.6-9 KEV) Spectral Properties, ApJ, 514, 772

Inui, T., Matsumoto, H., & Tsuru, T. G., et al., 2005, Chandra Observation of the Starburst Galaxy NGC 2146, PASJ, 57, 135

Irwin, J. A. & Sofue, Y., 1996, NGC 3628: The Nuclear Molecular Disk and Expanding Molecular Shells, ApJ, 464, 738

Kenninutt, R. C., Jr., 1998, Star Formation in Galaxies Along the Hubble Sequence, ARA&A, 36, 189

Matsushita, S., Kawabe, R., & Matsumoto, H., et al., 2000, Formation of a Massive Black Hole at the Center of the Superbubble in M82, ApJ, 545, 107

Matsushita, S., Kawabe, R., & Kohno, K., et al., 2005, Starburst at the Expanding Molecular Superbubble in M82: Self-induced Starburst at the Inner Edge of the Superbubble, ApJ, 618, 712

Nakai, N., Hayashi, M., & Handa, T., et al., 1987, A Nuclear Molecular Ring and Gas Outflow in the Galaxy M82, PASJ, 39, 685

Sakamoto, K., Aalto, S., & Wilner, D. J., et al., 2009, P Cygni Profiles of Molecular Lines Toward Arp 220 Nuclei, ApJL, 700, 104

Sanders, D. B., Mazzarella, J. M., & Kim, D. -C., et al., 2003, The IRAS Revised Bright Galaxy Sample, AJ, 126, 1607

Strickland, D. K., Colbert, E. J. M., & Heckman, T. M., 2001, Another Intermediate-Mass Black Hole in a Starburst Galaxy? The Luminous X-Ray Source in NGC 3628 Reappears, ApJ, 560, 707

Strickland, D. K., Heckman, T. M., & Colbert, E. J. M., et al., 2005, A High Spatial Resolution X-Ray and Hα Study of Hot Gas in the Halos of Star-forming Disk Galaxies. II. Quantifying Supernova Feedback, ApJ, 606, 829

Tsai, A. -L., Matsushita, S., & Nakanishi, K., et al., 2009, Molecular Superbubbles and Outflows from the Starburst Galaxy NGC 2146, PASJ, 61, 237

Tsai, A. -L., Matsushita, S., & Kong, A. K. H., et al., 2012, First Detection of a Subkiloparsec Scale Molecular Outflow in the Starburst Galaxy NGC 3628, ApJ, 752, 38

Tully, R. B., 1988, Nearby Galaxeis Catalog, Cambridge: Cambridge University Press