JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
38: 169 ~ 172, 2005

ASIAA EXTRAGALACTIC STUDY WITH THE SMA

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(Received February 1, 2005; Accepted March 15, 2005)

ABSTRACT

We present CO(3-2), CO(2-1), and 230 GHz (1.3 mm) continuum images of nearby galaxies taken with the Submillimeter Array (SMA). Our main topic is to study the relation between higher-J molecular gas (e.g., CO J=3-2, 2-1) and nuclear activities (e.g., active galactic nuclei [AGNs] and starbursts). The nearby Seyfert 2 galaxy M51 shows strong CO(3-2) emission from the circumnuclear molecular gas, with an intensity twice as strong as that of the CO(1-0) emission. Strong CO(3-2) emission enhancement suggests that the circumnuclear molecular gas in M51 is warm and dense, which may be related to the AGN activities. Molecular gas in the nearby moderate starburst galaxy NGC 6946 is distributed along the large-scale bar or spiral arms and along the minibar, and the multi-J CO line images show very similar distribution to each other. For this galaxy, there is no clear enhancement in higher-J lines as seen in M51, which may be because NGC 6946 does not have clear AGN activities. Based on the results of these two galaxies, the physical conditions of the circumnuclear molecular gas may be related to the AGN activities. We also observed the nearby edge-on starburst galaxy NGC 3628 and the starburst/Seyfert composite galaxy NGC 4945 with the CO(2-1) line and 230 GHz (1.3 mm) continuum emission. These information will give us some hints for understanding the relation between nuclear activities and circumnuclear molecular gas and dust.

Key words : galaxies: individual (M51, NGC 6946, NGC 3628, NGC 4945) — galaxies: ISM — submillimeter

I. INTRODUCTION

The Submillimeter Array* (SMA; Ho, Moran, & Lo 2004), which is the world's first imaging submillimeter interferometer and consists of eight 6 m antennas, started deployment at the summit of Mauna Kea in 1999. As soon as it became possible, a testing and commissioning phase started, and it continued till the completion of the SMA construction in the end of 2003. Now the SMA is observing scientific sources with a proposal base.

Just after the testing and commissioning phase of the SMA started, we observed several galaxies with CO(3-2) and CO(2-1) lines to see the distributions and characteristics of these lines, and to find out the differences with the CO(1-0) line under various galactic activities (e.g., AGN and starburst activities). We also observed a low declination (Dec. ~ −49°) source that could not be observed from other millimeter interferometers so far. In this paper, we show the CO(3-2) and CO(2-1) lines and 230 GHz (1.3 mm) continuum images of several galaxies taken as the SMA early science and proposal-base science observations of the Academia Sinica, Institute of Astronomy and Astrophysics (ASIAA) SMA extragalactic group.

II. MULTI-J CO LINE IMAGES TOWARD THE CENTER OF GALAXIES

During the testing and commissioning phase, we observed the nearby (8.4 Mpc; Feldmeier, Ciardullo, & Jacoby 1997) Seyfert 2 galaxy M51 and the nearby (5.9 Mpc; Karachentsev, Sharina, & Huchtmeier 2000) star forming galaxy NGC 6946 as early science sources in the CO(3-2) and CO(2-1) lines.

Fig. 1 shows M51 CO(3-2) image (Matsushita et al. 2004) taken with the SMA, as well as the CO(1-0) image (Sakamoto et al. 1999) taken with the Nobeyama Millimeter Array (NMA). The CO(3-2) image shows strong circumnuclear molecular peak at the center and weak emission from the north-western arm region. It

Proceedings of *the 6th East Asian Meeting of Astronomy*, held at Seoul National University, Korea, from October 18-22, 2004.

*The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory (SAO) and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), and is funded by the Smithsonian Institution and the Academia Sinica.

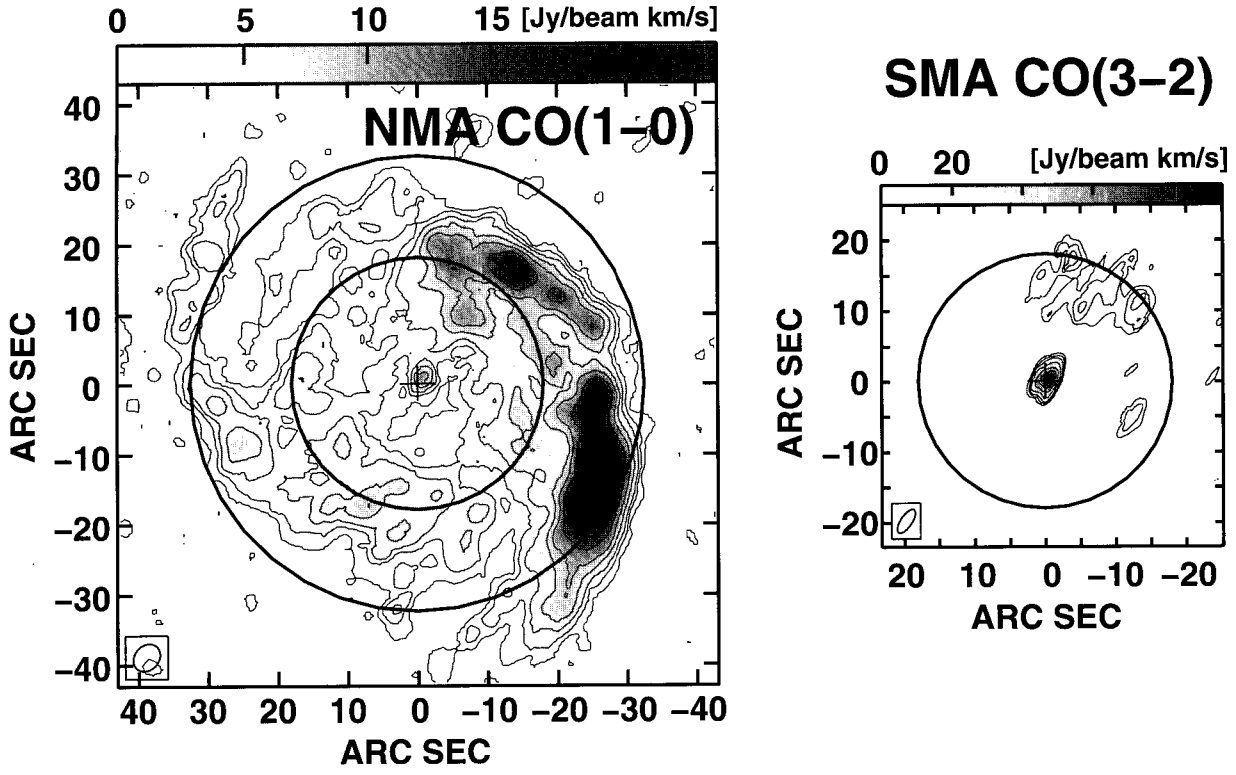

Fig. 1.— Multi-J CO line images of the central region of M51. The synthesized beam is shown in the bottom-left corner of each image. *Left:* CO(1-0) integrated intensity image taken from Sakamoto et al. (1999). The large and small circles indicate the full width at half maximum (FWHM) of the NMA and SMA primary beams, respectively. *Right:* CO(3-2) integrated intensity image taken from Matsushita et al. (2004). The circle indicates the FWHM of the SMA primary beam. Note the scales of CO(3-2) and (1-0) are matched each other.

is obvious that the circumnuclear molecular gas around the Seyfert 2 nucleus is strongly enhanced in the CO(3-2) image compared with that in the CO(1-0) image. Indeed, the CO(3-2) intensity is about twice as strong as that of CO(1-0) in temperature scale, which suggests that the molecular gas around the Seyfert nucleus is dominated by a warm and dense component (see Matsushita et al. 2004 for detailed discussion).

Fig. 2 shows NGC 6946 CO(3-2) and CO(2-1) images taken with the SMA (Mao et al. 2005, in prep.), as well as the CO(1-0) image (Sakamoto et al. 1999) taken with the NMA. The CO(2-1) and CO(1-0) images are very similar to each other, even for the extended structures. The extended structures are mainly located north and south of the nucleus, and these structures may be related to a bar (e.g., Ishizuki et al. 1990) or spiral arms (Regan & Vogel 1995). The CO(3-2) image shows only the central part due to the smaller full width at half maximum (FWHM) of the SMA primary beam of $\sim 36''$, but more detailed structures are possible to see because of the higher angular resolution. The strong central peak observed in CO(1-0) is resolved into several components in higher-J images. These peaks are aligned straight, and located along the minibar observed in the K-band image (Elmegreen, Chromey, & Santos 1998). The intensity of the central region does not show any enhancement in higher-J CO lines, in contrast with that in M51. The lack of intensity enhancement in higher-J CO lines suggests that the circumnuclear molecular gas in NGC 6946 is dominated by rather cold and diffuse gas.

Since M51 has a Seyfert 2 nucleus but there is no clear AGN activities in NGC 6946, the difference in the appearances of multi-J CO images may be related to the activities of galactic nuclei; AGN activities, such as strong radiation and jets, may affect circumnuclear molecular gas. Indeed, the radio jet from the AGN of M51 may be interacting with the circumnuclear molecular gas (Matsushita et al. 2004). However, this indication is based on a very limited number of galaxies, and further study is needed to find out the relation between molecular gas and AGN activities.

We also observed CO(2-1) emission from NGC 3628 and NGC 4945 (Fig. 3).

NGC 3628 is a nearby (7.7 Mpc; Tully 1988), edge-on (80°; Wilding, Alexander, & Green 1993) starburst galaxy, and is a member of the Leo Triplet. Optical images show a prominent dust lane along the galactic disk. The CO(2-1) emission is concentrated at the galactic center, and extended along the dust lane, which is sim-

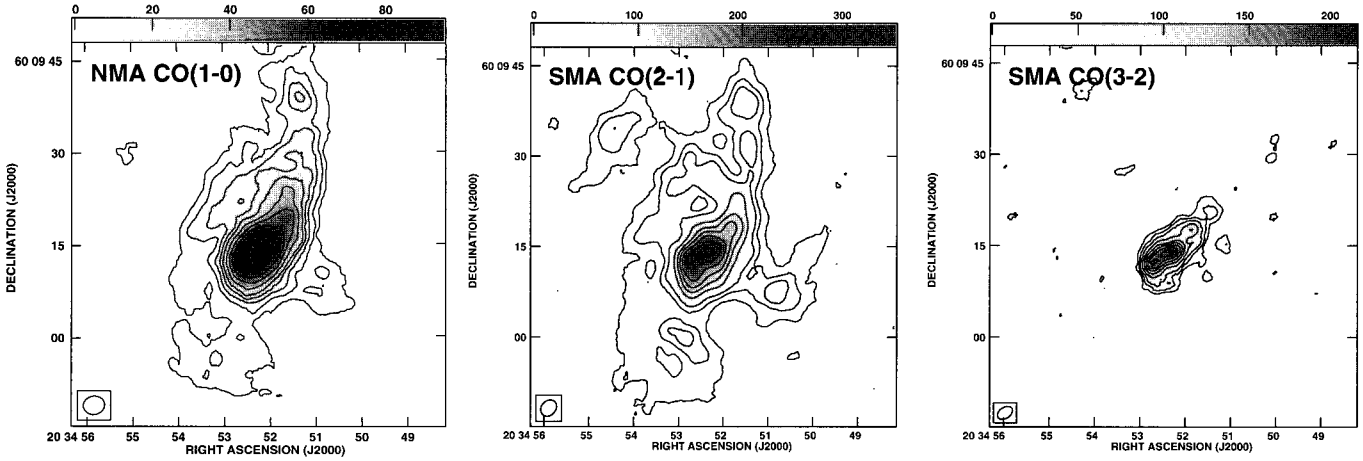

Fig. 2.— Multi-J CO line images of the central region of NGC 6946. The synthesized beam is shown in the bottom-left corner of each image. *Left:* CO(1-0) integrated intensity image taken from Sakamoto et al. (1999). *Middle:* CO(2-1) integrated intensity image taken with the SMA. *Right:* CO(3-2) integrated intensity image taken with the SMA. Note the scales of CO(3-2), (2-1), and (1-0) are matched each other.

ilar to the CO(1-0) distribution (Irwin & Sofue 1996).

NGC 4945 is a nearby (3.9 Mpc; de Vaucouleurs et al. 1981), edge-on (78°; Ables et al. 1987) starburst/Seyfert 2 composite galaxy, and is located at the southern hemisphere (Dec. $\sim -49°$). Since this galaxy is located at low declination, it has been observed only with single-dish millimeter/submillimeter telescopes so far. It is possible to observe sources with declination higher than $-51°$ with telescope elevation higher than 20°, because the SMA is located at the summit of Mauna Kea, whose latitude is about +19°. This image is, therefore, the first interferometric CO image of NGC 4945. The CO(2-1) emission is concentrated at the galactic center, and extended emission is also seen, mostly along the major axis of the galaxy.

There is no clear difference between the starburst galaxy NGC 3628 and the starburst/Seyfert 2 composite galaxy NGC 4945 in the integrated intensity images. We are now analyzing the gas kinematics to find out any common or different structures between these two galaxies. We also obtained ^{13}CO(2-1) and C^{18}O(2-1) line data, since the SMA has a 2 GHz bandwidth in each sideband and CO(2-1), ^{13}CO(2-1), and C^{18}O(2-1) can be obtained simultaneously. It will be interesting to compare these lines to see the difference in physical conditions of the molecular gas. As mentioned before, NGC 4945 is a starburst/Seyfert composite galaxy, so that studying this galaxy intensively may give us some hints about the effects of various galactic activities to the surrounding molecular gas.

III. CONTINUUM EMISSION IMAGES TOWARD THE CENTER OF GALAXIES

Submillimeter continuum emission from galaxies is usually dominated by the dust emission (see Condon 1992 for the meter to far-infrared wavelength spectrum energy distribution of starburst galaxy M82). However, the knowledge of dust, especially at high angular resolution study, is poor due to the lack of submillimeter interferometric continuum observations. The SMA has a 2 GHz bandwidth in one sideband, as mentioned above, so it is suitable to observe submillimeter continuum emission from galaxies.

We obtained 230 GHz (1.3 mm) continuum data for NGC 3628 and NGC 4945, and the continuum emission is clearly detected (Fig. 4), peaked at the nucleus of each galaxy. Most likely the 230 GHz continuum emission from these galaxies is dominated by the dust emission, but the free-free emission may also contribute because of the starburst activities. High-resolution spectrum energy distribution (SED) study using the SMA continuum data, together with high-resolution centimeter and millimeter continuum emission, will make this clear. In addition, the SED study in nearby galaxies will give us a hint about the variation of dust-to-gas mass ratio on the scale of giant molecular clouds (GMCs).

ACKNOWLEDGEMENTS

We thank all the past and present SMA staffs for designing, constructing, and supporting the SMA.

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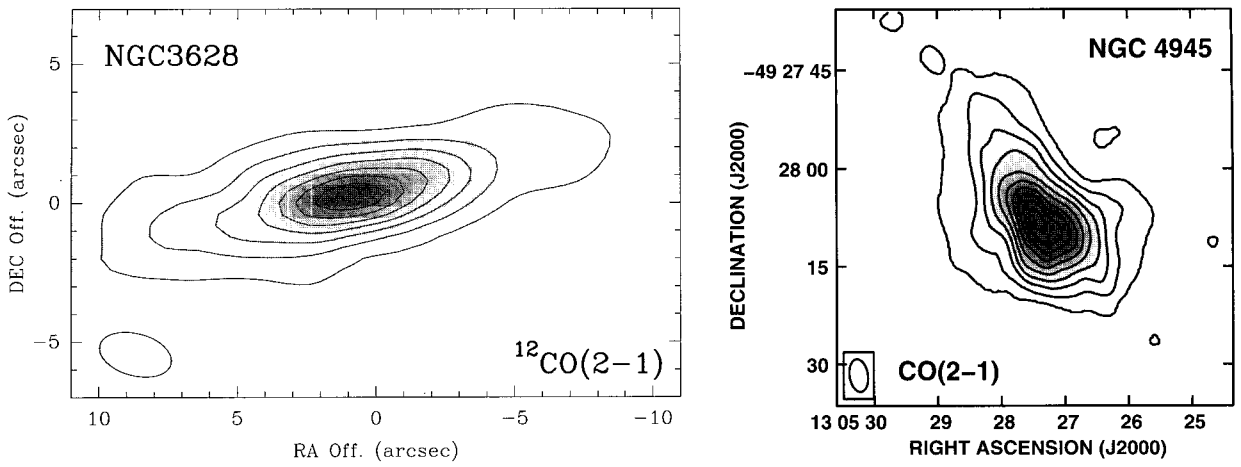

Fig. 3.— CO(2-1) images of the nearby edge-on galaxies NGC 3628 and NGC 4945. *Left:* CO(2-1) image of the starburst galaxy NGC 3628. *Right:* CO(2-1) image of the Seyfert/starburst composite galaxy NGC 4945.

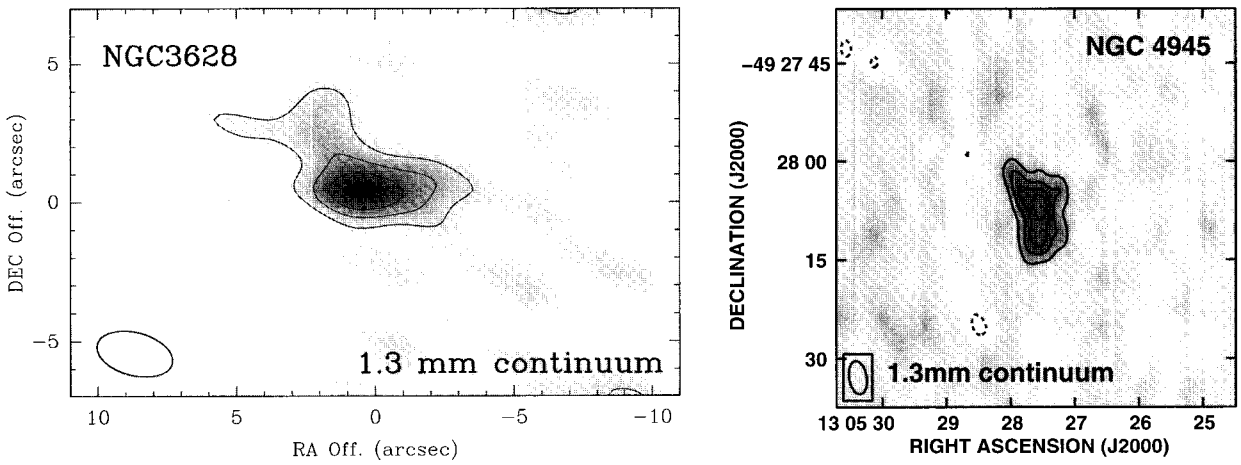

Fig. 4.— 230 GHz (1.3 mm) continuum images of the nearby edge-on galaxies NGC 3628 and NGC 4945. Both images are shown with the same size scale as Fig. 3. *Left:* 230 GHz continuum image of the starburst galaxy NGC 3628. *Right:* 230 GHz continuum image of the Seyfert/starburst composite galaxy NGC 4945.

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