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TRACING STAR FORMATION IN GALAXIES WITH MOLECULAR LINE AND CONTINUUM OBSERVATIONS

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Abstract. We report our recent progress on extragalactic spectroscopic and continuum observations, including HCN(J=1–0), HCO^+(J=1–0), and CN(N=1–0) imaging surveys of local Seyfert and starburst galaxies using the Nobeyama Millimeter Array, high-J CO observations (J=3–2 observations using the Atacama Submillimeter Telescope Experiment (ASTE) and J=2–1 observations with the Submillimeter Array) of galaxies, and λ 1.1 mm continuum observations of high-z violent starburst galaxies using the bolometer camera AzTEC mounted on ASTE.

1 Introduction

Massive stars are formed in the densest regions of molecular clouds; therefore, molecular spectroscopy of high-density tracers such as rotational lines of HCN and HCO^+ molecules in millimeter and submillimeter wavelengths provides us with essential details on the origin of massive stars in galaxies. They are free from dust extinction; hence, dust-enshrouded star formation can be unveiled using these observations. These spectroscopic observations are also expected to be a crucial diagnostic of nuclear power sources of dusty active galaxies, i.e., a probe to separately assess the nuclear star formation associated with active galactic nuclei (AGNs). Both AGNs and starbursts will have a strong impact on the surrounding dense interstellar medium (ISM) and form X-ray dominated regions

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(XDRs) and photo-dissociation regions (PDRs), respectively. However, they will have drastically different physical and chemical conditions that result in different molecular abundances and excitations between them (e.g., Maloney et al. 1996; Meijerink & Spaans 2005).

In this paper, we report our recent progress on extragalactic spectroscopic and continuum observations, including HCN(J=1–0), HCO^+(J=1–0), and CN(N=1–0) imaging surveys of local Seyfert and starburst galaxies using the Nobeyama Millimeter Array (NMA), high-J CO observations (J=3–2 observations using the Atacama Submillimeter Telescope Experiment (ASTE; Ezawa et al. 2004) and J=2–1 observations with the Submillimeter Array (SMA)) of galaxies, and λ 1.1 mm continuum observations of high-z violent starburst galaxies using the bolometer camera AzTEC (Wilson et al. 2008) mounted on ASTE.

2 Tracing star formation toward active nuclei

2.1 HCN-enhanced nuclei (HENs): toward a new diagnostic probe of nuclear energy source

The NMA imaging survey of HCN(J=1–0) and HCO^+(J=1–0) on local Seyfert and starburst galaxies (NMA-DENSS project; Kohno *et al.* 2001, 2007, 2008a; Kohno 2005) revealed the presence of "HCN-enhanced nuclei" or HENs among some of the Seyfert galaxies (Fig. 1). They show elevated HCN intensities with respect to CO and/or HCO^+ emissions; i.e., HCN/CO integrated intensity ratios ($R_{\rm HCN/CO}$)>0.3 and/or HCN/HCO^+ integrated intensity ratios ($R_{\rm HCN/HCO+}$)>1.5 in the brightness temperature scale. They are quite strange or intriguing because no clear evidence of a nuclear starburst is shown despite the fact that HENs are very luminous in the HCN emission (e.g., the lack of mid-infrared PAH emission, see table 1 of Kohno *et al.* 2007). The absence of HENs among starburst galaxies and the detections of highly excited high-J CO lines in HENs (e.g., CO(J=3–2)/CO(J=1–0) integrated intensity ratio of 1.9 ± 0.2 at the center of M 51, Matsushita et al. 2004; CO(J=2–1)/CO(J=1–0) of 1.9 ± 0.2 at the center of NGC 1097, Fig. 2) could also support the hypothesis that the elevated HCN(J=1–0) emission is closely connected to the presence of X-ray irradiated dense molecular medium or XDRs. This idea is successfully applied to local LIRGs/ULIRGs (e.g., Imanishi et al. 2007; Garcia-Burillo et al. 2007), although further studies will be required to understand the gap between the observations and theories (e.g., Yamada et al. 2007).

2.2 CN(N=1–0) in local starburst and Seyfert galaxies

We have also started a pilot survey of the CN(N=1–0) emission toward nearby starburst and Seyfert galaxies using NMA. The CN emission is another strong and important tracer of dense molecular gas after HCN and HCO^+ (Aalto et al. 2002; Riechers et al. 2007), and CN/HCN integrated intensity ratios ($R_{\rm CN/HCN}$) are expected to be enhanced significantly in the PDRs (Boger & Sternberg 2005) and XDRs (Lepp & Dalgarno 1996; Meijerink et al. 2007). One of our goals is to ob-

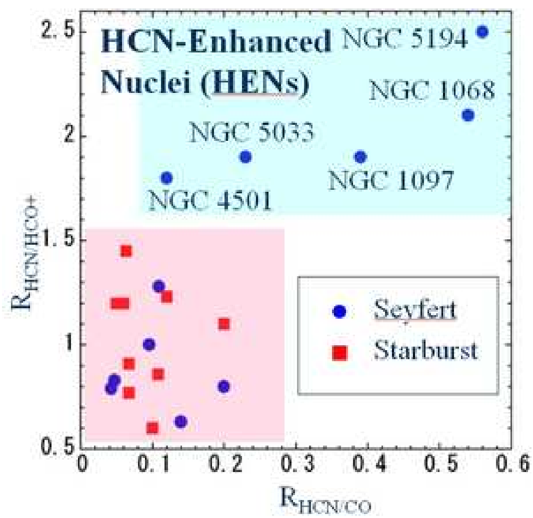

Fig.1. The distributions of the observed $R_{\rm HCN/CO}$ and $R_{\rm HCN/HCO+}$ ratios at the center of a few 100 pc regions of nearby Seyfert and starburst galaxies. Some of the Seyfert galaxies exhibit enhanced HCN(J=1–0) emission with respect to HCO^+(J=1–0) and/or CO(J=1–0) intensities (HENs). HENs are never observed among starburst galaxies.

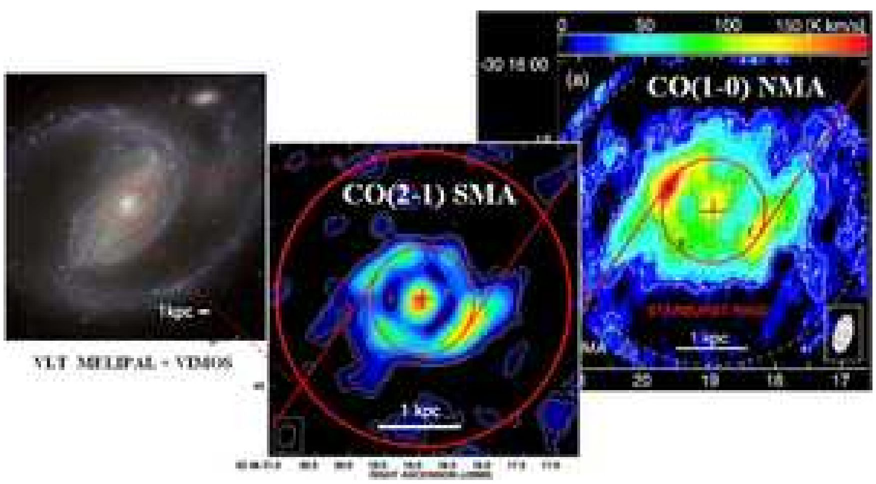

Fig.2. High-resolution integrated intensity images of CO(J=2–1) and CO(J=1–0) in the central kpc regions of NGC 1097 (Hsieh et al. 2007; Kohno et al. 2003). The CO(J=1–0) emission is dominated by the circumnuclear starburst ring (indicated by a red circle), whereas a strong peak emerges at the center in CO(J=2–1).

tain spatially resolved CN maps and to compare them with our existing HCN maps; this will allow us to understand the relative importance of PDR and XDR on the CN abundance. The instantaneous bandwidth of the NMA spectrocorrelator (1024 MHz; Okumura et al. 2000) enables us to observe $J=\frac{3}{2}-\frac{1}{2}$ and $J=\frac{1}{2}-\frac{1}{2}$ lines (consisting of hyperfine structure lines) simultaneously. Their ratios (hereafter $R_{(\frac{3}{2}-\frac{1}{2})/(\frac{1}{2}-\frac{1}{2})}$) can be used to estimate their opacities.

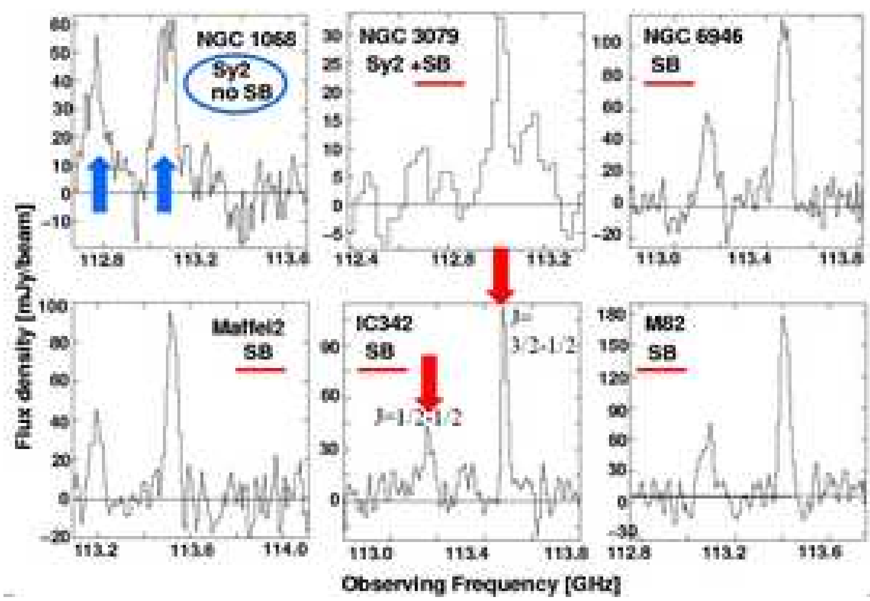

Fig.3. A part of CN(N=1–0) spectra in the central regions of local starburst and Seyfert galaxies taken with the NMA in the D-configuration (the observing beam sizes are typically $\sim 6''$).

Our preliminary results are presented in Fig. 3. All observed starburst galaxies (including NGC 3079, which hosts an AGN accompanied with a nuclear starburst) show an $R_{(\frac{3}{2}-\frac{1}{2})/(\frac{1}{2}-\frac{1}{2})}$ of $\sim$3 (i.e., optically thin), implying that CN(N=1–0) emission can be a useful measure of mass or abundance of dense ISM. On the other hand, $R_{(\frac{3}{2}-\frac{1}{2})/(\frac{1}{2}-\frac{1}{2})}$ was found to be close to unity (1.4 $\pm$ 0.15 within the central $r < 3''$) at the center of NGC 1068, suggesting that these lines are almost optically thick. This could be due to a significant increase in CN abundance at the center of NGC 1068, a prototypical giant XDR (Usero et al. 2004).

We then computed the $R_{\rm CN/HCN}$ values for two positions of NGC 1068, i.e., the center and the circumnuclear starburst region. There was no significant difference in the $R_{\rm CN/HCN}$ values between the nucleus and starburst region ($R_{\rm CN/HCN}$ was around 1.5 for both positions). This could indicate that *both* CN and HCN abundances are significantly elevated in the XDR of NGC 1068. Again, these results appear somewhat inconsistent with theoretical predictions (e.g., Meijerink et al. 2007), and we do require further studies both observationally and theoretically.

3 Tracing star-forming dense ISM in the disk regions of galaxies

We have conducted CO(J=3–2) imaging observations of nearby star-forming galaxies (ADIoS project; Kohno et al. 2008b; Muraoka et al. 2007; Tosaki et al. 2007) in order to depict star-forming dense molecular material in the disk regions of

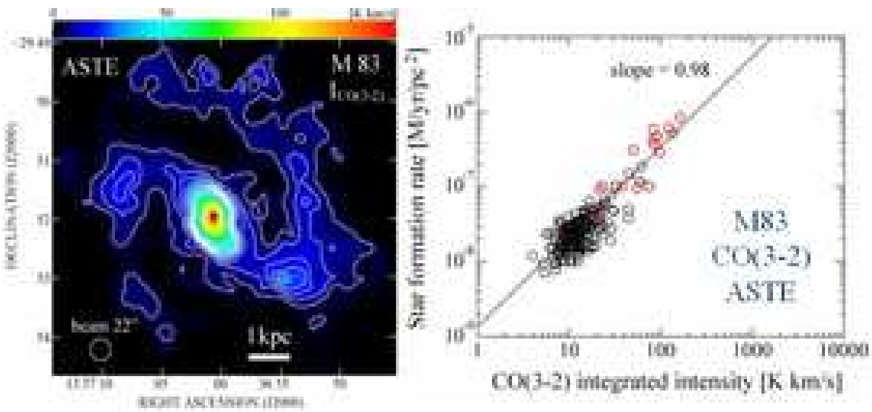

Fig.4. (Left) The CO(J=3–2) integrated intensity map of the central $5' \times 5'$ region of the barred spiral galaxy M 83 (Muraoka *et al.* in prep). (Right) The correlation diagram between the observed CO(3-2) integrated intensities and surface densities of SFRs derived from extinction-corrected Hα luminosities based on MIPS 24 μm data (Calzetti et al. 2007). See also Komugi *et al.* (2007).

galaxies, where high-density tracers such as HCN and HCO^+ molecules are very weak. Even with the single pixel receiver of ASTE 345 GHz band, the excellent atmospheric conditions of Atacama, good performance of the antenna and receiver, and efficient OTF mapping mode (Sawada et al. 2008) enable us to rapidly produce wide area CO(J=3–2) maps. Based on these data, a tight and linear connection between star formation rates (SFRs) and the amount of dense molecular gas traced by the CO(J=3–2) emission is revealed (Fig. 4).

4 Tracing hidden violent star formation in the early Universe

To uncover the hidden dusty massive star formation in the early Universe, we have started a deep λ 1.1 mm continuum imaging survey toward various blank fields and biased regions (such as proto-cluster forming regions around high-z radio galaxies, and so on) using the 144-pixel bolometer camera AzTEC (Wilson et al. 2008) mounted on ASTE. A typical map size is $12' \times 12'$ or wider, and a typical 1 σ noise level is $\sim$1 mJy or lower, allowing us to investigate large scale distributions/structures of SMGs (i.e., $\sim$ a few 10 Mpc scales) with a sufficient sensitivity to detect hyper luminous IR galaxies (i.e., $L_{\rm IR} > 10^{13} L_\odot$) in the early Universe.

One of the deep images obtained is presented in Fig. 5. Our preliminary combined analysis with AKARI 90 μm data suggests most of these sources are lying high-z ($z > 1$).

In the Lyα selected proto-cluster region SSA 22, about a 390 arcmin^2 region was deeply observed. We found a very poor spatial correlation between the detected 1.1 mm sources and the Lyα sources (LAEs and LABs), which was consistent with a previous finding in the TN J1338-1942 field (De Breuck et al. 2004). In spite of

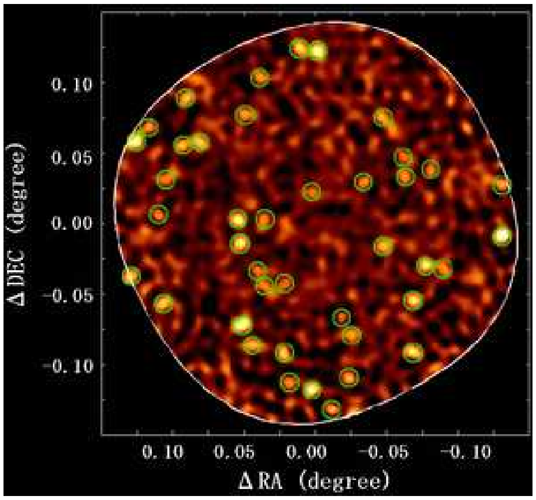

Fig.5. An example of λ 1.1 mm images taken with the AzTEC on ASTE (Hatsukade et al., in prep.). A $\sim$200 arcmin^2 region was observed with a sensitivity of $\sim$0.5 mJy toward a part of AKARI Deep Field South (ADF-S), where an extensive infrared deep survey has been conducted using the AKARI satellite (Matsuhara et al. 2006). More than 20 high significance (S/N > 4) sources have been detected. The beam size of AzTEC/ASTE is $\sim 28''$.

such a poor overlap between SMGs and LAEs, we found that the bright 1.1 mm sources are concentrated around the density peak of LAEs, i.e., a possible excess of number density of SMGs around the LAEs' density peak can be observed in our data. Further analysis, including the multiwavelengths follow-up observations to obtain constraints on the source redshifts, is in progress.

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