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MOLECULAR GAS AND RADIO JET INTERACTION: A CASE STUDY OF THE SEYFERT 2 AGN M51

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ABSTRACT

We observed multiple CO transition lines and the HCN(1-0) line at $\sim 1''$ (~ 34 pc) or higher resolution toward the Seyfert 2 nucleus of M51 using the IRAM Plateau de Bure Interferometer (PdBI) and the Submillimeter Array (SMA). All the images show very similar overall molecular gas distribution; there are two discrete clouds at the eastern and western sides of the nucleus, and the western cloud exhibits an elongated distribution and velocity gradient along the radio jet. In addition, high HCN(1-0)/CO(1-0) brightness temperature ratios of about unity have been observed, especially along the radio jet, similar to those observed in shocked molecular gas in our Galaxy. This strongly indicates that the molecular gas along the jet is shocked, that the radio jet and the molecular gas are interacting, and the jet is entraining both diffuse (CO) and dense (HCN) molecular gas outwards from the circumnuclear region. This is the first clear imaging of the outflowing molecular gas entrained by the AGN jet, and showing the detailed physical status of outflowing molecular gas. Since a relatively high HCN(1-0)/CO(1-0) ratio has been observed in the high velocity wing of ultraluminous infrared galaxies, it can also be explained by a similar mechanism to those we describe here.

Key words: M51 (NGC 5194): Seyfert nucleus: molecular gas: jet: outflow

1. INTRODUCTION

After the discovery of polarized broad optical ionized lines, which are the typical line properties of type 1 Seyfert galaxies, toward the type 2 Seyfert galaxy NGC 1068 (Antonucci & Miller, 1985), it is generally believed that both types 1 and 2 Seyfert galaxies are essentially the same object, but viewed from different directions. In this unified model both Seyfert galaxies host a supermassive black hole at the center, surrounded by a dusty disk or torus. The type 1 Seyfert galaxies are viewed face-on and the type 2 edge-on. After this discovery, many molecular gas observations have been made using millimeter arrays, and indeed, some of the early observations succeeded in imaging a strong molecular gas concentration toward Seyfert nuclei with a smooth velocity gradient at a spatial resolution of a few hundred pc (e.g., type 2 Seyfert NGC 1068: Jackson et al. 1993, type 2 Seyfert M51: Kohno et al. 1996). Similar results have been found even in recent observations (e.g., radio galaxy Centaurus A: Espada et al. 2009, type 1 Seyfert NGC 1097: Hsieh et al. 2008, type 2 Seyfert NGC 4945: Chou et al. 2007, Seyfert galaxy survey: Sani et al. 2012). In addition, this velocity gradient is often seen perpendicular to the jet axis, if observations are possible. These observations suggest that there seems to be a few hundred pc scale molecular gas disk or torus around a supermassive black hole and jets emanating perpendicular to this disk or torus, which matches the above unified model very well.

Recent high spatial resolution molecular gas observations at a spatial resolution of a few tens of pc toward nearby Seyfert galaxies, on the other hand, show very different features. Ten pc resolution observation of circumnuclear molecular gas toward the nucleus of M51 (Matsushita et al., 2007) shows a molecular cloud elongated along radio jets with a velocity gradient along the jets. This velocity gradient matches well with that of the [O III] emission along the jets (Bradley et al., 2004), suggesting that the molecular gas is entrained by the jets and outflowing from the Seyfert nucleus. Similar features have also been observed toward the type 2 Seyfert nuclei of NGC 1068 (Krips et al., 2011; García-Burillo et al., 2014) and NGC 1433 (Combes et al., 2013), once they has been observed at a spatial resolution of ten pc scale. On the other hand, some galaxies show infalling molecular gas (e.g., type 1 Sefert NGC 1097: Davies et al., 2009; Fathi et al., 2013), even toward a galaxy that shows outflowing motion at larger scales (NGC 1068: Müller Sánchez et al., 2009). These results indicate that the features that have been observed at large scales do not reflect the nature that has been revealed at small scales. Small scale features are more closely related to the nuclear activity. It is therefore critical to observe with high spatial resolution to reveal the relation between molecular gas and the nuclear activity.

M51 (NGC 5194) is one of the nearest type 2 Seyfert galaxies (7.1 Mpc; Takáts & Vinkó, 2006), which has a strong HCN concentration toward the nucleus (Kohno et al., 1996). Since HCN is strongly enhanced relative to CO or HCO^+, it is suggested that strong X-ray emission from the Seyfert nucleus enhanced the HCN abundance (Kohno et al., 2001, 2008a,b). However, since past HCN observations did not have high enough resolution to resolve the structures, it is still not clear what really caused the HCN enhancement. Here, we present $\sim 1''$ ($\sim$ 34 pc) resolution observations of the HCN(1-0) line toward the nucleus of M51 to resolve the structure and kinematics of dense molecular gas around the type 2 Seyfert nucleus.

2. DENSE MOLECULAR GAS OUTFLOW FROM THE M51 NUCLEUS

We obtained the CO(3-2) image using the Submillimeter Array (SMA) and the HCN(1-0) image using the IRAM Plateau de Bure Interferometer (PdBI). We had already obtained CO(1-0) and CO(2-1) images using PdBI in past observations (Matsushita et al., 2007). We then matched the shortest *uv* length for our CO(1-0), CO(3-2) and HCN(1-0) data for the quantitative comparisons. Since the CO(2-1) data have a very different *uv* coverage from the other data, we did not include it in the quantitative comparisons.

All the integrated intensity images show very similar features (Figure 1); there are two primary clumps, one in the west side of the nucleus (S1), which is elongated in the north-south direction, and another in the east side (S2), which is almost a point source. Kinematics (i.e., intensity-weighted velocity field maps) also show similar features (Figure 2); the S1 clump exhibits an obvious velocity gradient along the elongated north-south direction, with blueshifted velocites at the north and redshifted velocities at the south. The S2 clump, on the other hand, exhibits a slight velocity gradient along the east-west direction with blueshifted velocites at the west and redshifted velocities at the east. These results indicate that all the molecules, from diffuse to dense molecular gas, have the same structure and kinematics at the center of M51.

The S1 clump is elongated along the radio jets from the nucleus, and has a similar velocity gradient as that

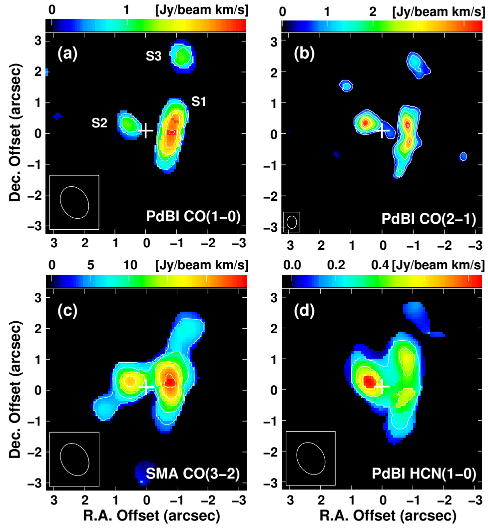

Figure 1. Integrated intensity images of (a) CO(1-0) line taken with PdBI, (b) CO(2-1) line with PdBI, (c) CO(3-2) line with SMA, and (d) HCN(1-0) line with PdBI. The CO(1-0) and CO(2-1) data are from Matsushita et al. (2007). The *uv* coverages and the beam sizes ($1.''10 \times 0.''85$, P.A. $= 31°$) are matched for all the images, except the CO(2-1) map ($0.''40 \times 0.''31$, P.A. $= 0°$), which has a significantly different *uv* coverage from the others. The beam size is shown at the bottom-left corner of each image. Central cross in each image indicates the location of the nucleus that is determined from the peak of the 8.4 GHz continuum peak position of R.A. $= 13^{h}29^{m}52.^{s}7101$ and Dec. $= 47°11'42.''696$ (Hagiwara et al., 2001; Bradley et al., 2004). Molecular clump names are labeled in (a). Contour levels are as follows: (a) 2, 4, 6, 8, and 10 $\times$ 0.248 Jy beam^{-1} km s^{-1}. (b) 1, 3, 5, 7, 9, and 11 $\times$ 0.334 Jy beam^{-1} km s^{-1}. (c) 2, 4, 6, 8, and 10 $\times$ 2.21 Jy beam^{-1} km s^{-1}. (d) 2, 4, and 6 $\times$ 0.109 Jy beam^{-1} km s^{-1}.

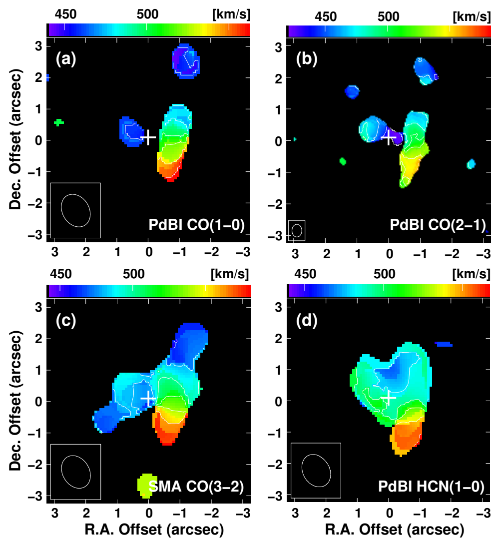

Figure 2. Intensity-weighted velocity field images of (a) CO(1-0) line, (b) CO(2-1) line, (c) CO(3-2) line, and (d) HCN(1-0) line. Contour levels are as follows: (a) 460, 480, 500, ..., 560 km s^{-1}. (b) 440, 460, 480, ..., 540 km s^{-1}. (c) 460, 480, 500, ..., 560 km s^{-1}. (d) 480, 500, 520, 540, and 560 km s^{-1}. Other information is the same as in Figure 1.

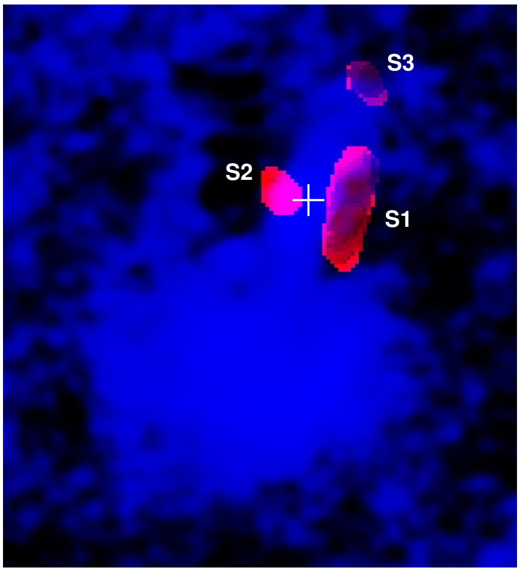

Figure 3. HCN(1-0)/CO(1-0) line ratio map (red) overlaid on the radio jet map (blue; Crane & van der Hulst, 1992). Intensity of the jet is strongly enhanced to show the relation between the ratio and the jet. It is clear that the location of the high ratio in the S1 clump is well overlapped with the radio jet.

of the [O III] emission line, which is associated with the radio jets (Bradley et al., 2004). Matsushita et al. (2007, 2004) concluded that the S1 clump is entrained by the jets and outflowing from the nucleus. The above results indicate that not only the diffuse molecular gas, which is traced by the CO molecule, but also dense molecular gas, which is traced by the HCN molecule, is outflowing from the nucleus.

Since the S2 clump is not related to the outflow, it is out of the scope of this paper; refer to Matsushita et al. (2014) for the detailed nature of the S2 clump.

3. SHOCKED MOLECULAR GAS IN THE MOLECULAR OUTFLOW

To see the properties of the molecular outflow, we first made the HCN(1-0)/CO(1-0) line ratio map. Since the *uv* coverages and the beam sizes have been already matched, we simply divided the two maps, but only used pixels where both CO and HCN lines are detected with more than 3σ. Figure 3 displays the HCN/CO ratio map (red) together with the radio jet map (blue; Crane & van der Hulst, 1992). The S1 clump shows a clear trend for the HCN/CO ratio; the ratio closer to the jets is higher, and it decreases as the distance from the jets increases. The ratio reaches about unity at the jet side, and decreases to about 0.3 at the far side from the jets. The overall average of the S1 clump is 0.6. The region that has the high ratio of about unity is clearly overlapping with the radio jet, and it is highly possible that the jet - molecular gas interaction caused the high ratio.

A high HCN/CO ratio of unity has never been observed in extragalactic sources, but it has been observed in Galactic sources, in the molecular outflows of young stellar objects; the low mass star forming region in the dark cloud L1157 exhibits a molecular outflow, and the HCN(1-0)/CO(1-0) line ratio in the outflow is 0.9 (Umemoto et al., 1992). Since this region is far away from the core, and is a purely molecular outflow (i.e., no contamination), they concluded that this high ratio is due to shocks. A high ratio of $0.4 - 0.5$ has also been observed in the high velocity outflow of Orion-KL (Wright et al., 1996). The lower ratio in the Orion-KL outflow is probably due to the complicated nature of high mass star forming regions compared to low mass star forming regions. These similarities indicate that the high HCN/CO ratio in the S1 clump is due to shock caused by the interaction between the radio jets and the molecular gas. This strongly supports the idea that the S1 clump is a molecular outflow entrained by the jets.

Although a high HCN/CO ratio of about unity has not been observed toward any other galaxies, a high ratio of ~ 0.6 has been observed in the unresolved high velocity wing of the ultraluminous infrared galaxy Mrk 231 (Aalto et al., 2012), suggesting that a similar mechanism is occurring there. Similar high ratios have also been observed toward other nearby Seyfert galaxies (e.g., Kohno et al., 2008a; Krips et al., 2007, 2011), and these galaxies may also have similar outflowing molecular gas near their nuclei, although high spatial resolution study is needed to confirm this.

4. CONCLUSIONS

We successfully imaged the HCN(1-0) emission line from the central $\sim 3''$ of the type 2 Seyfert galaxy M51 at a resolution of $\sim 1''$ (~ 34 pc), and compared with CO lines. The HCN(1-0) line is strongly enhanced compared to the CO lines in the outflowing molecular gas clump that is entrained by the radio jets. Such enhancement has been observed in the molecular outflows from young stellar objects, in particular in shocked regions. This indicates that the outflowing gas in M51 is affected by shocks caused by the radio jet - molecular gas interaction. Similar HCN enhancement has been observed in other outflows in galaxies, so the molecular gas in those galaxies is probably experiencing similar shocked conditions.

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