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Aperture Synthesis HCN Observations of M51 : Dense Molecular Disk around a LLAGN

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We performed aperture synthesis HCN(J=1→0) observations of M51 using the Nobeyama Millimeter Array with spatial resolutions of 6″ (corresponding to 290 pc at D = 9.6 Mpc). Higher resolution (4″) HCN images were also made to resolve the structure of the circumnuclear region.

We detected intense HCN emission in the central region (r $<$ 200 pc) where the depression of the CO emission is reported. The 4″ resolution HCN maps revealed a rotating dense molecular disk (the nuclear disk) whose rotation axis (position angle $\sim 160°$) is aligned to the direction of the nuclear jet (position angle $\sim 165°$), not to the rotation axis of the galactic plane. The radius of the nuclear disk is 70 pc and the rotation velocity of the nuclear disk is estimated to be $36(\sin i)^{-1}$ km s^{-1} at r = 70 pc, where i is the inclination angle of the nuclear disk. The HCN/CO integrated intensity ratios exceed 0.3 inside r = 140 pc, which is a factor of 10 larger than those of the spiral arm region (r $>$ 280 pc). The high HCN/CO ratio means that large fraction of the molecular gas is dense enough to excite HCN(J=1→0) emission ($n_{H_2} > 10^4$ cm^{-3}). The column density of molecular hydrogen toward the nucleus was estimated to be $N_{H_2} > 1.5 \times 10^{23}$ cm^{-2}, which plausibly accounts for the large absorption of X-ray observed with GINGA. These results suggest that the 100 pc scale molecular disk plays a role for the obscuration of weak Seyfert activity in M51.

INTRODUCTION

M51 is a bright Sbc galaxy with impressive grand-design spiral arms and recent observations suggest the presence of weak Seyfert activity in M51; VLA observations clearly depict the structure of the bidirectional jet along the north to south direction (Ford *et al.* 1985, Crane and van der Hulst 1992). At hard X-rays, the existence of a low luminosity AGN (LLAGN) with a L_X(2-20 keV) = $1.2 \pm 0.6 \times 10^{41}$ ergs s^{-1} was found with the GINGA observation (Makishima *et al.* 1990). It was also suggested that there is a large amount of absorption ($N_H = 4.2 \pm 1.5 \times 10^{23}$ cm^{-2}) toward the nucleus, which obscures the weak Seyfert nucleus.

Due to the proximity (9.6 Mpc) and low inclination of the galactic disk (almost face on; 20°), M51 is an appropriate object to study the distribution and physical condition of molecular gas around a LLAGN. In this contribution, we report the interferometric HCN($J=1\rightarrow0$) image of M51 taken with the Nobeyama Millimeter Array (NMA).

OBSERVATIONS AND RESULTS

The central region of M51 was observed in the $J=1\rightarrow0$ line of HCN using the NMA through the observing run of April 1994 - May 1994 and January 1995 - March 1995. Six 10-m antennas were equiped with SIS recievers. The system noise temperature was 500 K (SSB). The observations were made using three configurations (D, C, and AB).

Figure 1 shows the HCN integrated intensity map at 6″ resolution. Remarkably intense HCN emission was detected in the central r < 200 pc region, whereas a deficiency of CO emission was reported in the same region (*e.g.* Kawabe *et al.* 1990). The spiral structure of dense gas at the western arm is also clearly depicted.

We calculated the HCN/CO integrated intensity ratio using the previously performed NMA observations of CO emission (Kawabe *et al.* 1990). The HCN map recoves almost all of a single-dish flux, whereas the CO map samples about 70%, thus we assumed that the missing flux of CO was distributed uniformly within the field of view. The HCN/CO ratio in the central r < 140 pc area exceeds 0.3, that is a factor of 10 larger than in the spiral arms, where it is 0.03 - 0.05. This extremely high HCN/CO ratio in the central region indicates that the physical condition of the circumnuclear gas is considerably different from that in the spiral arm regions.

We show 4″ resolution HCN images in Figure 2; the blue-shifted (V_{LSR} = 445 - 477 km s^{-1}) and the red-shifted emission (V_{LSR} = 477 - 509 km s^{-1}), is superposed on the VLA map of the radio jet (Crane and van der Hulst 1992).

DISCUSSION

We found that the gas kinematics in the central r < 200 pc region can be understood as the rotation of a gas disk whose rotation axis is just aligned to the radio jet. The peaks of the blue and the red-shifted emission shown in Figure 2 are spatially symmetric with respect to the radio continuum peak (*i.e.* the nucleus) and these peaks indicate a velocity shift with P.A. $\sim$ 70°, which is just perpendicular to the direction of the nuclear jet (P.A. $\sim$ 165°; Ford *et al.* 1985, Crane and van der Hulst 1992). These results seem to indicate the existence of a rotating dense molecular disk around the nucleus (hereafter *the nuclear disk*). This picture is also supported by the Hubble Space Telescope (HST) image of M51; the dust lanes referred as the "X-shape" has been reported (Ford 1993) and we found that the major axis of the dense molecular disk lies along the nearly same direction as the more prominent dust lane, which is interpreted to be a dusty disk observed edge-on.

We estimate the H_2 column density of the nuclear disk using our observational data. Supposing equivalent excitation temperatures for HCN and CO, the observed HCN/CO brightness temperature ratio is

$$\frac{T_{HCN}}{T_{CO}} = \frac{f_{HCN}(1-\exp(-\tau_{HCN}))}{f_{CO}(1-\exp(-\tau_{CO}))}, \quad (1)$$

where T is the observed brightness temperature, f is the beam filling factor, and τ is the opacity of emission. From observations of Galactic molecular clouds, it is likely that $\tau_{CO} \gg 1$ and ($f_{HCN} < f_{CO}$). Therefore, it is expected that $\tau_{HCN} > 0.36$ for the observed HCN/CO brightness temperature ratio ($\sim$ HCN/CO intensity ratio, because these emission has almost same velocity width) = 0.3.

Consequently, the HCN column density is estimated to be $N_{HCN} > 3.0 \times 10^{15}$ cm^{-2} using the derived opacity, $\tau_{HCN} > 0.4$. The excitation temperature is taken to be 30 K in this calculation because T_{ex} is estimated to be 30 - 40 K for the dense molecular components in the nuclear region (Garcia-Burillo *et al.* 1993). The column density is estimated to be $N_{H_2} > 1.5 \times 10^{23}$ cm^{-2}, using a Galactic [HCN]/[H_2] abundance ratio of 2×10^{-8}. This column density plausibly accounts for the large column density of X-ray absorbing material toward the nucleus, $N_H = 4.2 \pm 1.5$ $\times 10^{23}$ cm^{-2}, suggested by GINGA (Makishima *et al.* 1990). This means that dense molecular gas surrounding the nucleus of M51 would be responsible for obscuration of the weak Seyfert activity.

The radius of the nuclear disk of M51 is $\sim$ 70 pc and the rotation velocity is estimated to be 36 $(\sin i)^{-1}$ km s^{-1} at r = 70 pc, where i is the inclination angle of the nuclear disk. A 100-pc scale dense gas disk is also reported in the type-2 Seyfert galaxy NGC 1068 (Jackson *et al.* 1993, Tacconi *et al.* 1994). The radii of the disks in M51 and NGC 1068 are substantially larger than that of proposed obscuring torii (r $\sim$ a few pc), implying that such a 100 pc scale dense gas/dust disk plays a role in obscuring the nuclear activity.

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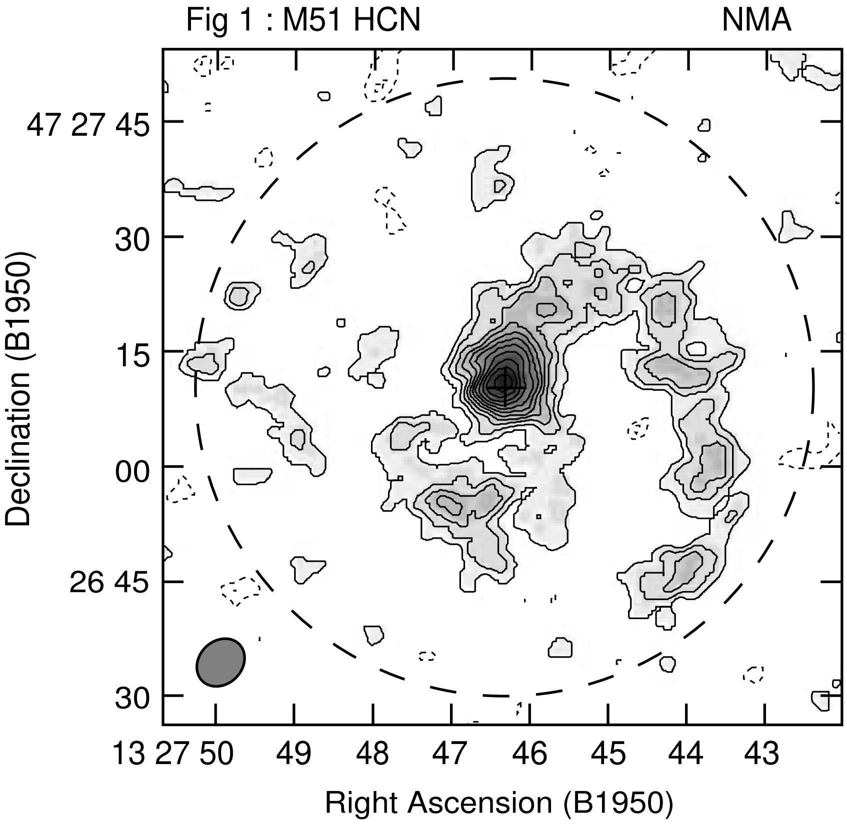

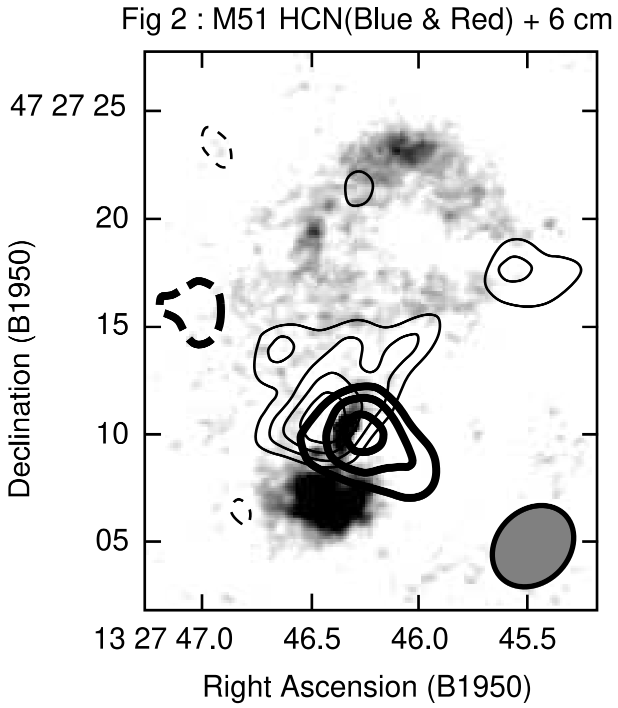

Fig. 1 : Integrated intensity map of HCN(J=1-0) emission over a velocity range from V(LSR) = 393 to 540 km/s in the central 4 kpc region of M51. The synthesized beam is 7.1" x 5.8" with a P.A. of 138 deg, indicated as a filled ellipse. The field center, shown by a cross, is the position of the radio continuum peak (Ford et al. 1985) and the field of view is 84" denoted by a dashed circle. The contour levels are -3,-2,2,3,4,5,6,7,8,9,10,11, and 12 sigma where 1 sigma = 0.44 Jy/beam km/s =1.7 K km/s. The primary beam attenuation is not corrected in this map.

Fig. 2 : The HCN emission separated by velocity. The blue-shifted emission (445 - 477 km/s) is represented by thin contours, and the red-shifted emission (477 - 509 km/s) by thick contours. The 6 cm VLA image of the radio jet (Crane and van der Hulst 1992) is superposed as a halftone. The synthesized beam is 4.4" x 3.6" (P.A. 130 deg). The contour levels are -2,2,3,4, and 5 sigma, where 1 sigma = 9.0 mJy/beam = 89 mK.