AMMONIA IMAGING OF THE DISKS IN THE NGC 1333 IRAS 4A PROTOBINARY SYSTEM

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ABSTRACT

The NGC 1333 IRAS 4A protobinary was observed in the ammonia (2, 2) and (3, 3) lines and in the 1.3 cm continuum with a high resolution (about 1.0") for the (2, 2) line and 0.98" for the (3, 3) line, when the imaging was done with a natural weighting. The 1.3 cm continuum data produced a synthesized beam of 1.02" x 0.91" and 71°, with a robust weighting.

The NGC 1333 IRAS 4 region was observed using the Very Large Array (VLA) of the National Radio Astronomy Observatory in the NH$_3$ (2, 2) and (3, 3) lines (23722.6336 and 23870.1296 GHz, respectively) and in the λ = 1.3 cm continuum. Twenty-five antennas were used in the C-array configuration on 2004 March 5. The continuum was observed for 20 minutes at the beginning and for 10 minutes at the end of the observing track, and the NH$_3$ lines were observed for 5 hr in the midsection of the track. For each of the NH$_3$ lines, the spectral windows were set to have 64 channels with a channel width of 0.049 MHz, giving a velocity resolution of 0.62 km s$^{-1}$. The 1.3 cm continuum, the observations were made in the standard K-band continuum mode (22.5 GHz or λ = 1.33 cm).

The phase tracking center was ($\alpha$, $\delta$) = (03°29′10.41″, 31°13′32.2″) in J2000.0. The nearby quasar 0336+323 (PKS 0333+321) was observed to determine the phase and to obtain the bandpass response. The flux was calibrated by observing the quasar 0713+438 (QSO B0710+439) and by setting its flux density to 0.49 Jy, which is the average of the flux density measured within a day of our observations (VLA Calibrator Flux Density Database). Comparison of the amplitude gave a flux density of 1.97 Jy for 0336+323, and the flux uncertainty is ∼10%. To avoid the degradation of sensitivity owing to pointing errors, pointing was referenced by observing the calibrators at the X band (3.6 cm).

Maps were made using a CLEAN algorithm. The NH$_3$ data produced synthesized beams of FWHM = 0.97" x 0.94" and P.A. = 29° for the (2, 2) line and 0.98" x 0.95" and 47° for the (3, 3) line, when the imaging was done with a natural weighting. The 1.3 cm continuum data produced a synthesized beam of 1.02" x 0.91" and 71°, with a robust weighting.

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3. RESULTS AND DISCUSSION

Figure 1 shows the NH$_3$ (3, 3) line image with an angular resolution similar to the SiO outflow image of Choi (2005). While the NH$_3$ map shows clumpy structures around the outflows, the most striking feature is the compact structure associated with the central objects, which were not seen in the SiO map. (The outflows will be discussed separately in a future paper.) Figure 2 compares the NH$_3$ maps with the 1.3 cm continuum map, Table 1 lists the continuum parameters, and Figure 3 shows the NH$_3$ spectra. The deconvolved FWHM sizes of the NH$_3$ (3, 3) sources are 350 $\pm$ 260 AU (1.1 $\pm$ 0.8) for A1 and 260 $\pm$ 60 AU (0.8 $\pm$ 0.2) for A2, assuming a distance of 320 pc (de Zeeuw et al. 1999). Their compact nature suggests that the NH$_3$ lines are tracing accretion disks. This interpretation is especially strong in the case of A2 because the emission structure is elongated in the direction perpendicular to the main bipolar outflow. The position angle difference between the minor axis of the A2 disk and the outflow axis is $\sim$20°. In addition, the blue-/redshifted emission peaks of A2 are displaced in a way suggestive of a rotating disk (Fig. 2c).

### 3.1. Flux Anticorrelation

Comparisons of the NH$_3$ and the continuum maps reveal a remarkable anticorrelation: A1 is brighter than A2 in the continuum map, but it is the other way around in the NH$_3$ maps. For a quantitative analysis, we may define an NH$_3$-to-dust flux ratio $R = F(\text{NH}_3)/F(2.7 \text{ mm})$, which is the ratio of the total flux densities of the NH$_3$ (3, 3) line to the 2.7 mm continuum. The flux densities from the NH$_3$ data shown in Figure 2b and

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### TABLE 1

| Source | Peak Position | Flux Density* |
|--------|---------------|---------------|
| A1     | 03 29 10.51   | 1.44 ± 0.01   |
| A2     | 03 29 10.41   | 0.19 ± 0.01   |
| BI     | 03 29 12.00   | 0.36 ± 0.01   |

Note: Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* Flux densities at 1.3 cm in units of millijanskys, corrected for the primary beam response.

** Spectral index between 1.3 cm and 2.7 mm (Looney et al. 2000). The uncertainty in the absolute flux scale is 10%.
the 2.7 mm data of Looney et al. (2000) give $R(\text{A1}) = (7.1 \pm 1.1) \times 10^{-3}$ and $R(\text{A2}) = (4.8 \pm 0.7) \times 10^{-2}$. (The uncertainties were estimated by assuming a 10% uncertainty in flux scales.) That is, the NH$_3$-to-dust flux ratio of A2 is larger than that of A1 by a factor of 6.8. [If we use the 1.3 cm flux densities, $R(\text{A2})/R(\text{A1})$ is about 12.] Before making interpretations of the flux ratio as column density ratio, several factors affecting the flux densities should be considered.

First, can the line optical depth affect the flux ratio? Since the satellite hyperfine components were not covered in our observations, the optical depth cannot be deduced directly. The line profiles (Fig. 3), however, provide useful information. The spectra toward A2 have larger line widths and higher intensities than those of A1, which suggests that A2 may have relatively larger optical depths. In addition, the (2, 2) spectrum toward A2 shows a self-absorption dip, suggesting that the line may be optically thick. Therefore, if the line optical depth effects are considered, the degree of the anticorrelation would be severer.

Note, however, that there are alternative explanations for the line profiles. The line width difference can be explained if source A2 is a nearly edge-on disk and A1 is either a relatively more face-on disk or a static core. Also, the central dip of the spectra can be caused by a missing flux problem owing to large-scale structures. This issue can be addressed by future observations either with a higher angular resolution or with a spectral coverage wide enough to include the satellite hyperfine components.

Second, can the high NH$_3$ flux of A2 be caused by a peculiar excitation? The ratio between the (3, 3) and (2, 2) lines is not very useful for a quantitative analysis because they belong to different species, ortho-NH$_3$ and para-NH$_3$, respectively (Ho & Townes 1983). Even so, the (3, 3)–to–(2, 2) line ratio is similar in both sources (Fig. 3), suggesting that they have similar excitation conditions. In fact, the critical density of the NH$_3$ inversion transitions are low ($\sim 2 \times 10^5$ cm$^{-3}$; Ho & Townes 1983), and the NH$_3$ molecules are expected to be thermalized. Therefore, it is unlikely that the difference in the NH$_3$-to-dust flux ratio is caused by a peculiar excitation condition of NH$_3$ in one of the sources.

Finally, can the dust properties affect the flux ratio? The spectral index in principle provides some information on the dust opacity index. The spectral index of A1 is slightly lower than that of A2 (Table 1), but these values cannot be used directly because the contributions from free-free emission to the 1.3 cm fluxes are not known. Flux measurements at submillimeter wavelengths are desirable for estimating the dust opacity index. Girart et al. (2006) presented a 345 GHz map that resolves the continuum peaks, but their beam size was not quite small enough for measuring the total flux densities of each source separately. Therefore, this issue cannot be resolved with the currently available data, and we presume that the dust opacity index of the two sources are similar. Another variable that can affect the flux ratio is the dust optical depth. The dust is most likely optically thin at centimeter wavelengths, but it could be optically thick at submillimeter. While the measurement of the optical depth is not easy, if this effect is significant, it would affect the stronger source, A1, more severely. Therefore, a correction for the dust optical depth, if necessary, would also make the degree of the anticorrelation severer.

In summary, the results of our observations suggest that the IRAS 4A system contains two sources of contrasting conditions. The NH$_3$-to-dust flux ratio of A2 is $\sim 7$ times larger than that of A1, and the NH$_3$-to-dust column density ratios may be different by a similar factor, or by a larger factor if the optical depth of the line or the dust emission is considered. The difference between the two sources is huge, considering that they are accreting matter from a common protostellar envelope, and must be caused by the physical and chemical processes happening in each component.

### 3.2. Possible Explanations

There are two possible explanations for the flux/column density anticorrelation of the IRAS 4A system. The main difference between them is the evolutionary status of A1. While A2 is almost certainly a protostar, the nature of A1 is less certain:

1. A1 and A2 are roughly coeval, the NH$_3$ lines trace two accretion disks, and the anticorrelation is caused by a peculiar physical/chemical condition in one of them. In this scenario, A2 is a protostar driving the northeast-southwestern outflow, and A1 is another protostar driving the southern outflow. (We will elaborate on this model in § 3.3.)

2. A1 and A2 are in quite different stages of evolution, the NH$_3$ maps show a (spherical) dense core (A1) and an accretion disk (A2), and the anticorrelation is an indication of the difference in their nature. In this scenario, A2 is an actively accreting protostar, and A1 is a pre-protostellar object without an outflow activity. The strong millimeter continuum of A1 suggests a high concentration of dust. Nevertheless, the compact structure detected by interferometers suggests that A1 may not be a usual pre-protostellar object, either. Then A1 could be a transitional object, either a pre-protostellar object on the verge of collapse or a protostar immediately after the onset of collapse.

We prefer the first explanation for several reasons. First, A1 is bright in the centimeter continuum (Reipurth et al. 2002). This free-free emission is a clear sign of outflow activity. Second, comparison of the mass estimates over a range of size scale indicates that A1 has a steep density gradient. [For example, the mass of the IRAS 4A envelope within a diameter of $\sim 9''$ is $3.2 \ M_\odot$, when scaled to the distance of 320 pc (Sandell & Knee 2001). The mass of A1 within a $\sim 2.5''$ box is $1.9 \ M_\odot$, when scaled to 320 pc and scaled by the flux ratio between A1 and A2 (Looney et al.}
The anticorrelation between the gas and the dust flux densities of the IRAS 4A disks has important implications on the star formation process. The standard models of accretion are based on the cases of a single central star, and the mass accretion rate is mainly related to the density structure of the protostellar envelope (Shu et al. 1987). In binary systems, however, as the IRAS 4A system shows, even though the two components share a common envelope, each of them can evolve in a distinctive way. That is, there is an important controlling agent that may be lacking in the case of isolated star formation. A possibly crucial factor is the distribution and (mis)alignment of angular momentum (Bodenheimer 1995). If the mass outflow rate is a good indicator of the mass accretion rate, A2 may be growing much faster than A1, by accreting matter through an active disk.

One interesting issue to be addressed in the future is the NH$_3$ abundance. Does the high column density ratio of A2 mean an overall enhancement of gaseous molecules relative to dust? Or does it mean a selective enhancement of NH$_3$ (and related species) only? Estimating the degree of enhancement is difficult because comparison with CO lines cannot be interpreted easily owing to the complicated chemistry of nitrogen-bearing molecules (Charnley 1997) and the confusion with outflows. Currently there is no reliable estimates of NH$_3$ abundance in protostellar disks, and it is needed to make high-resolution images of the two disks in a variety of molecular lines.

Since planets do exist in multiple-star systems (Raghavan et al. 2006), our results have interesting implications for planet formation. If the A2 disk is indeed gas-rich/dust-poor, and if such a condition can persist until the planet-forming phase of the disk evolution, planetary systems produced in such disks may look very different from our solar system. We may speculate that, for example, such a system may strongly favor the growth of gas-giant planets. Thus, multiple-protostar systems can produce diverse types of planetary systems.

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2000). Then the density of A1 (average within a diameter of 820 AU) is higher than the density of the envelope (average within 2900 AU) by a factor of 26 ± 4.] Third, in the second scenario, the southern outflow might be driven by an unknown protostellar object, which is unlikely because NGC 1333 IRAS 4 is one of the most extensively observed regions of star formation near the Sun. Therefore, we suppose that both A1 and A2 are protostars. In the following section, we will discuss the implications of our observations based on the first explanation.

3.3. Peculiarity of the IRAS 4A2 Disk

The difference in the column density ratio suggests that one of the IRAS 4A disks is peculiar. There are several lines of evidence indicating that the A2 disk is unusually active. First, most of the water maser spots in this region are intimately associated with A2 (Fig. 2), and their velocities are close to the systemic velocity of the cloud core (Furuya et al. 2003; Park & Choi 2007), suggesting the existence of shocked gas in the A2 disk. Second, the outflow driven by A2 (northeast-southwestern bipolar outflow) is stronger than the one driven by A1 (southern outflow; Choi 2005; Choi et al. 2006), also suggesting that the outflow engine (the accretion disk) is more active in A2 than in A1. The northeast-southwestern outflow of IRAS A2 is one of the best collimated molecular outflows (Blake et al. 1995). Third, A2 seems to have an unusually large R-value. Comparison with other protostars may tell which disk is the peculiar one. Examples of protostellar disks detected in the NH$_3$ (3, 3) line are rare, but fortunately IRAS 4BI was detected. IRAS 4BI is a single protostar located within the field of view of our observations (Fig. 1). Measurements of the flux densities give $R$(BI) = (4 ± 2) × 10$^{-3}$, which is similar to $R$(A1) and suggests that A2 may be the abnormal one. Therefore, the A2 disk may be unusually gas-rich or dust-poor. Such a condition may be possible if the disk is very active or hot so that the dust grains infalling from the protostellar envelope may be destroyed and converted to gaseous molecules, probably via evaporation of molecules in the grain mantle.