ROTATING PROTOPLANETARY GAS DISK IN GG-TAU

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ABSTRACT A rotating gas disk was discovered around a T-Tauri star, GG-Tau, in Taurus by using the Nobeyama Millimeter Array (NMA) (Kawabe *et al.* 1993). To analyze the observed data, we have numerically calculated velocity profiles of CO emitted from protoplanetary gas disks by taking account of the line radiative transfer.

It is generally believed that the solar system was born from a disk of gas and dust, having a radius of ~ 40 AU and encircling the Sun about five billion years ago (e.g., Hayashi, Nakazawa, and Nakagawa 1985; Cameron 1985). Millimeter interferometric observations of HL-Tau, T-Tau, and DG-Tau, which are T-Tauri stars similar to the Sun, revealed gas disks with radii of a few thousands AU around the stars (e.g., Sargent and Beckwith 1987, 1991). Recently, Skrutskie *et al.* (1993) detected the $^{12}CO(J=1-0)$ emission toward GG-Tau using the Nobeyama 45 m telescope with a spatial resolution of 17" (2400 AU at the distance to GG-Tau, 140 pc). The velocity profile of the CO emission strongly suggests the existence of a rotating gas disk around GG-Tau.

To investigate the distribution and kinematics of the molecular gas found toward GG-Tau, we made aperture synthesis $^{12}CO(J=1-0)$ observations using NMA on April 2 and May 2 - 4 in 1992 (Kawabe *et al.* 1993). The size of the synthesized beam was 10" × 6" (P.A. = 138°) and the velocity resolution was 0.81 km·s^{-1}.

We have discovered a rotating gas disk around GG-Tau, and have derived several parameters of the gas disk as follows: The radius R_{disk} is larger than 500 AU; the inclination angle i is ~ 60° ; the rotation velocity, 0.8 km·s^{-1}/sin i at 500 AU, agrees with Kepler rotation around GG-Tau having a mass of 0.65 $M_\odot$; the gas kinetic temperature T is ~ 10 K at 500 AU; and the estimated mass of the disk, M_{disk} ranges from $1 \times 10^{-4} M_\odot$ (from total CO flux) to 0.4 $M_\odot$ (from kinematical consideration).

For the analysis of our observed data, we calculate velocity profiles of the ^{12}CO ($J=1-0$) line emitted from protoplanetary gas disks around young stars by taking the line radiative transfer into account (Omodaka, Kitamura, and Kawazoe 1992), based on the Kyoto model (Hayashi, Nakazawa, and Nakagawa 1985). The antenna temperature $T_A{}^*$ of the CO emission from a disk at a frequency ν is calculated by the following equation:

$$T_A^* = \frac{\ln 16}{2\pi k_B} \frac{\lambda^2}{HPBW^2} \frac{1}{D^2} \int_{disk} P_\nu(\theta, \phi) \kappa_\nu B_\nu(T) e^{-\tau_\nu} dV ,$$

where λ is the wavelength of the emission, k_B is the Boltzmann constant, $HPBW$ is the beam size of a telescope, D (= 140 pc) is the distance to the source, $P_\nu(\theta, \phi)$ is the beam pattern of a radio telescope, κ_ν is the absorption coefficient for the emission, $B_\nu(T)$ is the Planck function with a temperature T, and τ_ν is the optical depth along the line of sight. In this equation we assume the LTE condition for the CO emission. We adopt 9×10^{-5} as the abundance ratio of the ^{12}CO to H_2 molecules, and neglect the dust opacity.

First, we tried model fitting to the ^{12}CO profile detected toward GG-Tau by Skrutskie *et al.* (1993) with the 45 m telescope. In our model fitting, it was assumed that

the mass of GG-Tau is 0.65 $M_\odot$, and that the gas temperature varies as $13(r/500 \text{ AU})^{-0.5}$ K. Both the radius R_{disk} and inclination angle i of the disk were changed. The best fit result was obtained for R_{disk} = 900 AU and i = 67°, as shown by thin solid line in Fig. 1.

Next, we converted the calculated profile shown in Fig. 1 into the profile for the case of observations by NMA. The profile indicated by the broken line in Fig. 2 shows the converted profile. Furthermore, we changed the velocity resolution into 0.81 km·s^{-1}, and the corresponding profile is indicated by thin solid line. On the redshifted side, the observed profile agrees with our calculated profile within the uncertainty of the flux scale. On the blueshifted side, however, the observed profile is twice as high as the calculated one. This large difference may be explained by the following model: The disk is considered to be asymmetrical as observed by NMA, and the radii of the disk on the east and west sides are estimated to be ~ 2000 and 1000 AU, respectively (see Fig. 3). Since the beam size of the 45 m telescope is ~ 2000 AU, the single dish could not cover the entire disk, and only the redshifted part was covered. As a result, the observed velocity profile of CO becomes symmetric and shows the double-peaked feature (see Fig. 1). On the other hand, the field of view of NMA completely covered the disk, and the resultant velocity profile has an excess on the blueshifted side (see Fig. 2).
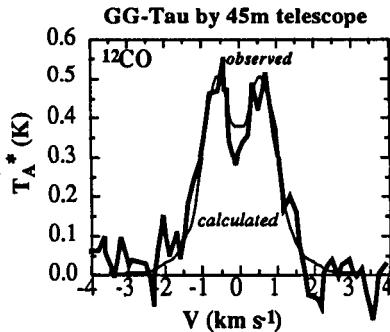

Figure 1. ^{12}CO(J=1-0) profile detected toward GG-Tau by the Nobeyama 45 m telescope (thick solid line) and a calculated profile (thin solid line).

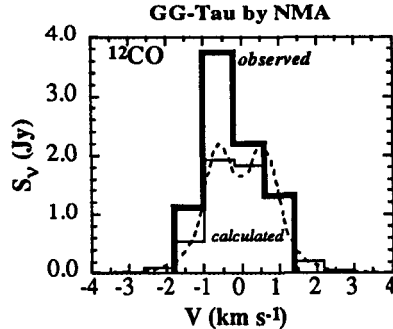Figure 2. ^{12}CO(J=1-0) profile observed by NMA (thick solid line) and a calculated profile (thin solid and broken lines).
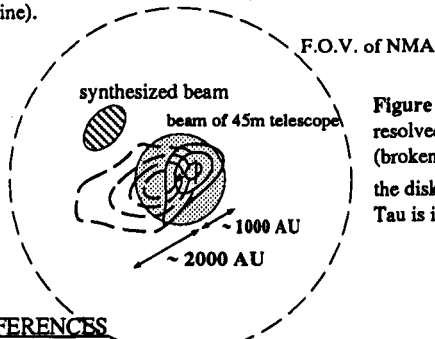

Figure 3. Protoplanetary disk around GG-Tau resolved by NMA. Contours indicate blueshifted (broken line) and redshifted (solid line) components of the disk at 5.7 and 7.3 km·s^{-1}, respectively, where GG-Tau is indicated at the center by a star.

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