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PECULIAR ROTATIONS OF MOLECULAR GAS IN M82: KEPLERIAN DISK AND SLOWLY ROTATING HALO

Y. SOFUE,[1] H.-P. REUTER,[2] M. KRAUSE,[2] R. WIELEBINSKI,[2] AND N. NAKAI[3]

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ABSTRACT

High-resolution, high-sensitivity observations of the CO ($J = 2 - 1$) lines in the galaxy M82 have revealed that the rotation of the gas disk is Keplerian, which suggests that the galaxy has no massive halo. The extended molecular gas halo, extending up to ± 2 kpc above the galactic plane, shows very slow rotation and indicates that the halo gas has been ejected from the central region in angular momentum conservation.

Subject headings: galaxies: individual (M82) — galaxies: ISM — galaxies: kinematics and dynamics

1. INTRODUCTION

The peculiar starburst galaxy M82 (NGC 3034) was one of the first galaxies detected in molecular lines. The galaxy has been extensively observed particularly in the CO lines, and a largely extended halo has been detected (Rickard et al. 1975; Solomon & de Zafra 1975; Olofsson & Rydbeck 1984; Young & Scoville 1984; Tilanus et al. 1991). Recent CO observations with large-aperture telescopes have given higher resolution, higher sensitivity maps, indicating a high concentration of molecular gas in the central starburst region (Nakai et al. 1987; Lo et al. 1987; Loiseau et al. 1988, 1990). Various peculiar characteristics of the molecular gas in M82 have been claimed to exist: a high-velocity outflow from the starburst region (Nakai et al. 1987; Sofue 1988 for a review), an extended halo with possibly slower rotation (Loiseau et al. 1988), or a possible decline of the rotation velocity in the outer disk (Young & Scoville 1984).

In this paper we present a high-sensitivity, wide-area map in the $^{12}CO(J = 2 - 1)$ line of M82, and discuss the kinematics, especially the slow rotation of the halo gas and a Keplerian rotation of the disk.

2. HIGH-SENSITIVITY CO OBSERVATIONS

The observations were made on 1990 November 1–4 using the IRAM 30 m telescope in good weather conditions. The telescope was equipped with two SIS receivers, and the system SSB noise temperatures including the atmospheric losses at 115 and 230 GHz were typically 700 and 800 K (in T_{mb}), respectively. The half-power beam widths were 13″ and 21″, corresponding to 205 and 400 pc at $J = 2 - 1$ and $1 - 0$ lines, respectively. We assume a distance of 3.25 Mpc (Tammann & Sandage 1968). The forward-spillover and main-beam efficiencies were 0.9 and 0.6, respectively, at 115 GHz, and 0.9 and 0.45 at 230 GHz (A. Sievers 1991, private communication).

The pointing calibration was done in continuum mode on the sources 0716+714 and 0923+392 using the 2 mm receiver. The alignment of this receiver with the 230 GHz one was better than 1″, while the 115 GHz receiver was misaligned by 4″–5″. The pointing errors during observations were about 3″–4″ for 230 GHz and 5″–7″ for 115 GHz.

At both bands we used a filter bank spectrometer of 512 channels × MHz. In addition an AOS was operated at 115 GHz simultaneously, allowing an independent control of baseline variations and calibration. We used the standard chopper wheel method, which switched on an off positions. The calibration of the spectra was done by observing Ori A IRC 2 once a day, which had peak $T_{mb} = 130$ K for the $^{12}CO(J = 1 - 0)$ line and 170 K for $^{12}CO(J = 2 - 1)$. The spectra were centered on the adopted systemic velocity, $V_{LSR} = 220$ km s^{-1}, so that the spectrometer covered a velocity range from -112 to 553 km s^{-1} at 230 GHz. The intensities used in this paper are in T_{mb}, and can be related to T_A^* by $T_{mb} = 2.0 T_A^*$ at 230 GHz. Although both data of the $^{12}CO(J = 2 - 1)$ and $^{12}CO(J = 1 - 0)$ lines were obtained with almost equal quality, we present the higher resolution $^{12}CO(J = 2 - 1)$ data in the present paper. A detailed comparison of the data from the two transitions and related discussion of the physical properties of the gas will be given in a forthcoming paper.

3. THE MOLECULAR HALO AND ITS SLOW ROTATION

Figure 1 (Plate 1) shows the integrated intensity distribution of the $^{12}CO(J = 2 - 1)$ line, $I \equiv \int T_{mb}\, dv$, as superposed on an optical photograph of M82. The CO map shows two central peaks, which correspond to the 200 pc molecular ring (Lo et al. 1987; Nakai et al. 1987). Pronounced here is a largely extended molecular gas halo. Such a large halo has been indicated by earlier observations, but the present observations show much more detail, not only of the spatial distributions but also in the kinematical structures.

From the CO data we could obtain position-velocity diagrams parallel to the major axis at various altitudes (Z-direction) to investigate the rotation characteristics in the halo. In Figure 2 we show some of the position-velocity diagrams represented symmetrically with respect to the galactic plane at $Z = 0$, ± 380, and ± 950 pc. We also obtained the distribution of the mean CO velocity (the velocity field) as shown in Figure 3 for the central 1 kpc area.

First of all from Figure 2 we may notice a systematic shift of the central velocities toward positive (red) in the northern halo, while velocities in the southern part are blueshifted, This is also recognized as the significant inclination of the velocity contours around the systemic velocity in Figure 3. This systematic shift has been simply interpreted due to an outflow of molecular gas at several hundred km s^{-1} perpendicular to galactic plane (Nakai et al. 1987). Furthermore the shift observed in the

[1] Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181, Japan.
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Germany.
[3] Nobeyama Radio Observatory, Minamimaki, Minamisaku, Nagano 384-13, Japan.

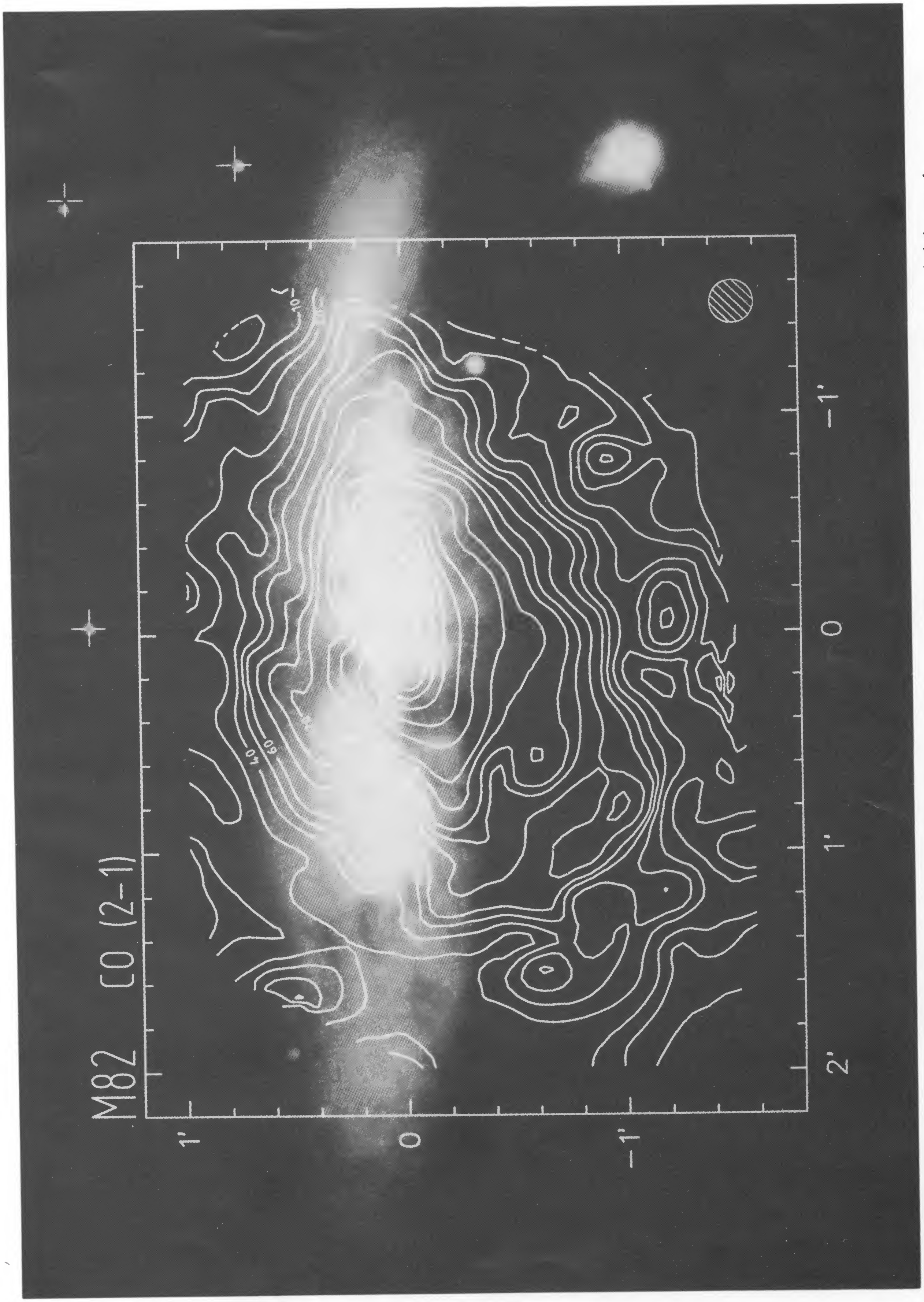

FIG. 1.—Distribution of the integrated intensity (in K km s^{-1}) of the ^{12}CO($J = 2 - 1$) line emission of the galaxy M82 as superposed on an optical photograph

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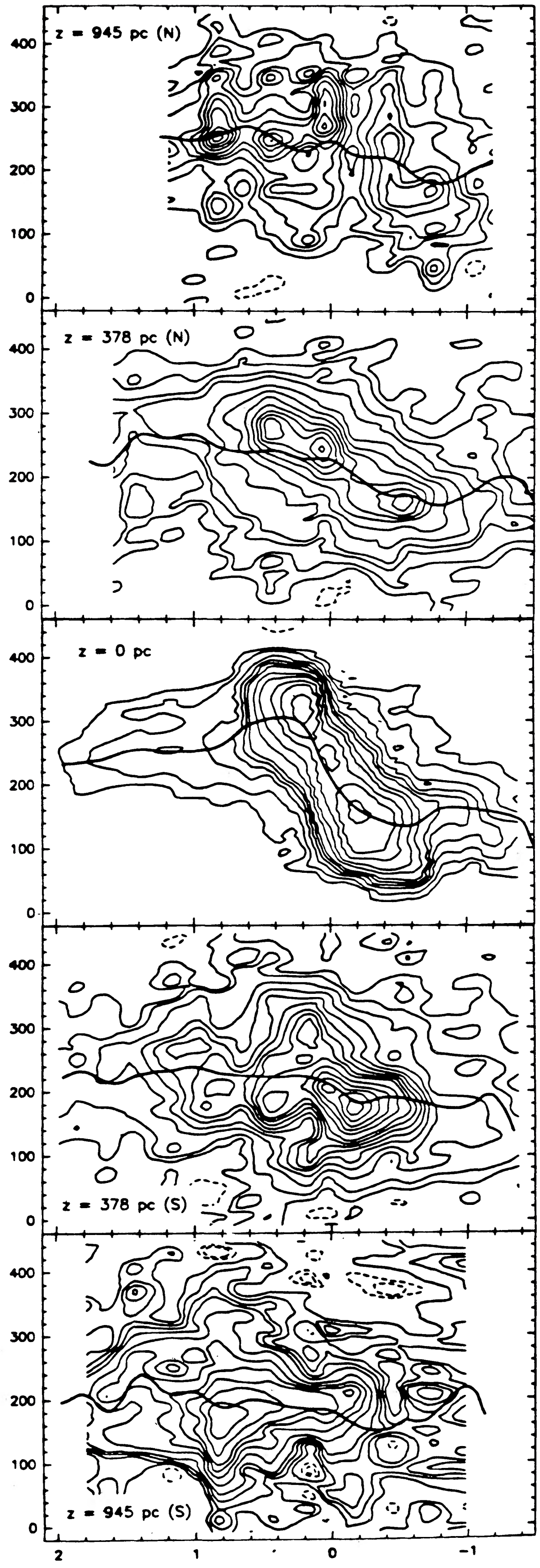

FIG. 2.—Position-velocity diagrams parallel to the major axis at Z offsets of $Z = 0$, ± 380, and ± 950 pc ($\simeq 0$, $\pm 0\rlap{.}'4$, $\pm 1'$).

mean velocity at the high-Z region is consistent with the peculiar noncircular motion of the H I halo (Gottesman & Weliachew 1977).

The most conspicuous feature in Figures 2 and 3 is that the rotation of the halo gas significantly slows down with the distance from the disk plane. This has been already noticed by Loiseau et al. (1990) in their data for smaller area. At the galactic plane ($Z = 0$), a maximum rotation of about $V_{rot} = 100$ km s^{-1} is observed at $X = \pm 200$–500 pc. At $Z = 200$–400 pc at the same longitude, however, the rotation is about half the disk rotation. At $Z = 1$ kpc, we have a very slow rotation of about $V_{rot} = 20$–30 km s^{-1}, and at $Z = \pm 1.4$ kpc we see almost no rotation.

Such a significant decrease in the rotation velocity with the height Z is consistent with the outflow model proposed by Nakai et al (1987) that the halo gas has been supplied from the central region and expanded in angular momentum conservation. One might consider an alternative interpretation that the round CO distribution in Figure 1 is due to an apparent projection of a highly inclined, circularly rotating disk. In this case, an apparently slower rotation at high Z (on the sky) due to the inclined outer disk. However, deep optical photographs (e.g., Lynds & Sandage 1963) show that the galaxy is nearly edge-on up to its farthermost edge, so that this interpretation requires a CO disk significantly warped from the optical (stellar) disk. We think, the former interpretation is more reasonable in view of the fact that M82 is a starburst galaxy.

4. KEPLERIAN ROTATION OF THE DISK: NO MASSIVE HALO?

Figure 4 shows a position-velocity diagram along the major axis up to ± 4 kpc from the center. The diagram is consistent with the previous result by Young & Scoville (1984), which covered a region of $-3 < X < 3$ kpc with a spatial resolution of 45″. The rotating ring appears in Figure 4 as the two strong concentrations at $X = \pm 200$ pc, $V = \pm 100$ km s^{-1} with

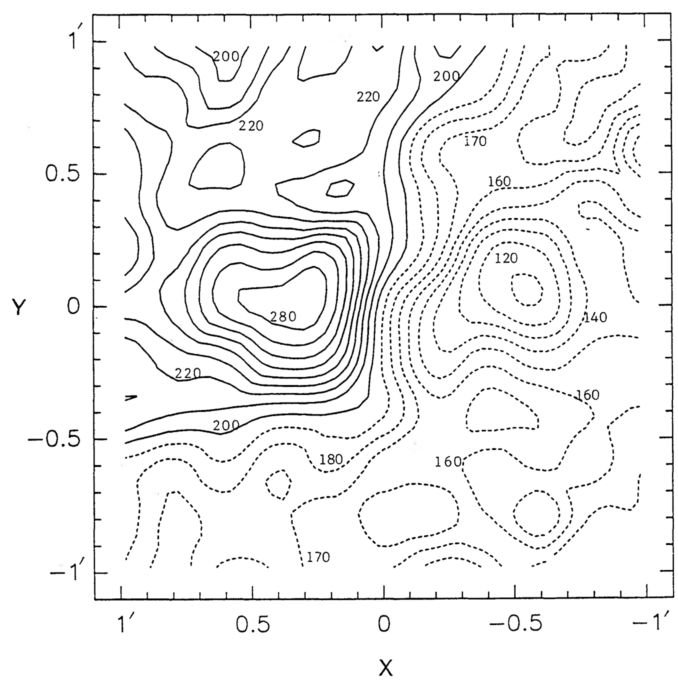

FIG. 3.—Mean velocity field for M82 as obtained from the CO($J = 2 - 1$) observations. LSR velocities in km s^{-1} are indicated on the contours.

respect to the systemic velocity $V_{LSR} = 220$ km s^{-1}. Obviously the gas distribution as well as the rotation are asymmetric with respect to the nucleus.

The systemic velocity as determined for the rotating ring alone is 220 km s^{-1}, which does not represent a systemic velocity of the outer parts. The systemic velocity determined for the gas beyond $r = 500$ pc is 190 km s^{-1}, and the same value is obtained toward $(X, Y) = (0, 0)$ in Figure 3.

The most remarkable kinematical characteristic along the galactic plane as seen in Figure 4 is that the rotation velocity decreases with the distance from the nucleus. The velocity decreases more rapidly in the eastern half (positive X) and tends to the systemic velocity (190 km s^{-1}) near the edge at $X \sim 2$–4 kpc. In the western disk, the velocity shows a similar behavior, but slows down slightly more gradually, and the slow rotation is obvious particularly at $X = -3$ to -3.6 kpc, where the velocity is approximately the same as the systemic velocity. Hence, in so far as the region at $r > 3$ kpc is concerned, the apparent rotation of the galactic disk is slower than 20–40 km s^{-1}.

The decrease in the apparent rotation with radius may indicate either (1) a Keplerian motion of the outer disk, (2) an warped outer disk, or (3) almost free contraction of outer gas disk with a small angular momentum.

The second possibility may be denied in view of the same argument as in the previous section. The third possibility seems also unlikely: if the gas is infalling freely, its radial velocity toward the center must be as large as $+100 \sim 200$ km s^{-1} for the near side of the disk and -100 to -200 km s^{-1} for the far side, so that the velocity dispersion at $X = -2$ to $+2$ kpc must be as large as 200–400 km s^{-1}. But this is not observed. Hence, the first possibility seems most plausible. Although it is also likely that the gas disk is contracting by such a mechanism as the bar-shock, accretion due to the tidal interaction with M81 (e.g., Noguchi 1988), the radial velocity of the accretion, which takes several rotations, must be much smaller than the free-fall velocity in a quasi-balance with the gravity, or it is quasi-Keplerian.

In Figure 4 we have superposed Keplerian rotation curves by dashed lines as simply calculated from $V_{rot} = \sqrt{GM/r}$ with (1) $M = 6 \times 10^9$ $M_\odot$ and (2) $M = 2 \times 10^9$ $M_\odot$, respectively. Here we assumed a systemic velocity of 190 km s^{-1}. The observed rotation can be reasonably approximated by Keplerian. From this fact we may be able to conclude that the galaxy has no significant massive halo. The total mass of the galaxy can be well constrained from the rotation velocity derived from the terminal velocity to be 1.0×10^{10} $M_\odot$, and the main part is confined within a 2 kpc radius region.

The rotation characteristics of M82 is thus obviously different from those found in normal spiral galaxies showing flat rotations (Rubin, Ford, & Thonnard 1980; Bosma 1981) and therefore having massive halos. Our result indicates the existence of such a type of galaxy which has no massive halo, and thus shows Keplerian rotation. There has been other evidence for declining rotation curves in the outer edges of galaxies (Rubin & Ford 1982; Casertano & Gorkom 1991). However, the later evidence from H I data is for more distant galactic disks at $r > \sim 10$–30 kpc, while our result indicates a "purer" Keplerian behavior beyond $r \sim 1$ kpc.

As to the origin of the Keplerian rotation of M82, we could suggest that the massive halo, which existed in the past, has been swept away during tidal interactions with the nearby galaxy M81. If the envelope of M82 has been tidally truncated during the past encounters with M81, we could estimate the perigalactic distance of the two galaxies, as the rotation curve of M82 shows that the outer disk beyond 2 kpc has been severely truncated. Therefore we may assume that the tidal force of M81 dominated over the gravity of M82 even at this radius, $r = r_t \sim 2$ kpc. Then the perigalactic distance between M82 and M81, R, can be related to their mass and r_t through $(r_t/R)^3 \sim M_{82}/M_{81}$, where M_{82} and M_{81} are the masses of the two galaxies. For $r_t \sim 2$ kpc, $M_{82} \sim 6 \times 10^9$ $M_\odot$ and $M_{81} \sim 10^{11}$ $M_\odot$, we obtain $R \sim 4$ kpc. The encounter was very close, and M82 has almost penetrated M81. This close and strong encounter may be the cause for the enhancement of starburst in M82 (e.g., Sofue 1988), as well as for the nonflat rotation curve of M81 (Bosma 1981). We also mention that M81 has a disturbed H I tail (Cottrell 1977; Gottesman & Weliachew 1977; van der Hulst 1979; Brouillet et al. 1991), which could be related to this encounter.

5. CONCLUSION

High-resolution and high-sensitivity observations of the CO($J = 2 - 1$) line of M82 have been made using the IRAM 30 m telescope. A wide area of $4' \times 4'$ around the galactic center has been mapped, and a strip as long as $\pm 4'$ (± 4 kpc) along the major axis has been observed. Results of the observations can be summarized as follows:

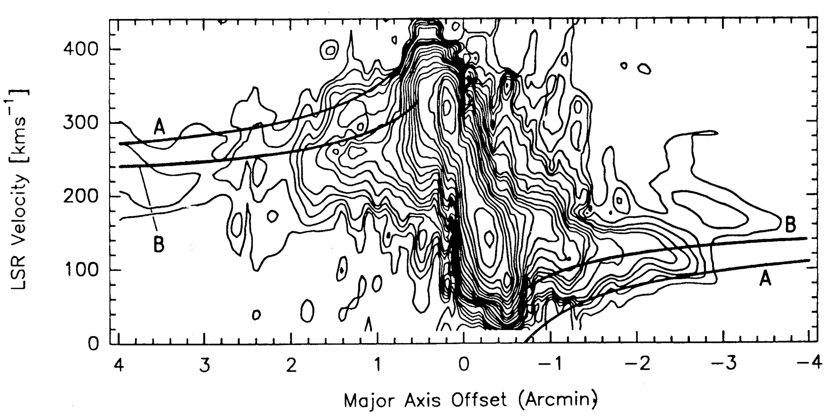

FIG. 4.—Position-velocity diagram along the major axis of M82 for the CO($J = 2 - 1$) line. Dashed lines show calculated Keplerian rotation for a point mass of (a) 1.0×10^{10} $M_\odot$ and (b) 2.0×10^9 $M_\odot$, where the systemic velocity of 190 km s^{-1} has been assumed for the outer disk regions. The contour levels are -0.4, 0.4, 0.8, 1.2, ... 2.0, 3, 4, 6, ... 12, 16, 20, 30, ... 100 in T_{mb}.

1. The largely extended, round-shaped molecular halo shows much slower rotation than the disk: This fact is consistent with a model that the molecular gas in the halo has been supplied from the nuclear region by an outflow associated with the starburst in angular momentum conservation.

2. The rotation within the galactic disk beyond $r > \sim 3$ kpc is as slow as 20–40 km s^{-1}, and the rotation velocity at $r > 1$ kpc is approximately fitted by a Keplerian law.

3. The Keplerian rotation of the galactic disk indicates that M82 has no massive halo. This could be due to truncation of a massive halo during a close encounter with the more massive galaxy M81 at a perigalactic passage as close as a few kpc.

In this paper we gave discussion based mainly on the $^{12}CO(J = 2 - 1)$ line. A full presentation of the results for the two transition lines ($J = 2 - 1$ and $1 - 0$) and their intercomparison will be given in a separate paper together with a detailed discussion of physical conditions of the molecular gas in M82.

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