Publ. Astron. Soc. Japan 34, 189–197 (1982)

Neutral Hydrogen in M31. III. The Warping of H I Disk

Takeyasu SAWA

Department of Earth Science, Aichi University of Education, Kariya, Aichi 448

and

Yoshiaki SOFUE*

Department of Physics and Astrophysics, Nagoya University, Chikusa-ku, Nagoya 464

(Received 1981 August 6; revised 1981 December 1)

Abstract

An overall feature of the warping of H I disk of M31 is obtained through an analysis of H I-line data by assuming cylindrical rotation. We further assume that the inner disk at galactocentric distance $R \leq$ 10 kpc is flat with an inclination of 77°. The warping from this flat disk plane amounts to 0.5–1.0 kpc in the region at $R \sim$20–30 kpc. There is a peculiar arm in the eastern outermost region at $R \sim$30–40 kpc which deviates 8 kpc from the galactic plane.

Key words: Galaxies; M31; Neutral hydrogen; Warping.

1. Introduction

In our previous papers on neutral hydrogen in M31 [Sofue and Kato (1981); Sawa and Sofue (1981); hereafter referred to as Papers I and II, respectively], we have shown that the observed 21-cm line profiles with the 100-m telescope by Cram et al. (1980) are well explained by a density-wave theory and that the multi-peaked line profiles are caused by different arms in the same beam area of resolution $9' \times 9'$. On the other hand, Emerson (1975) and Shane (1975) have found double-peaked profiles in a considerably wide area by their high-resolution observations. Since their beam widths are smaller than the arm interval in M31, Emerson (1975) claimed that two H I arms are overlapping along the line of sight, and proposed a warping of the H I disk.

Newton and Emerson (1977) constructed a warped disk model for M31 to explain the velocity anomalies and the displacement of the H I emission region from the major axis in distant regions at galactocentric distances $R \sim$25–30 kpc. However, they used H I gas distribution in very distant regions and only near the major axis. Whitehurst et al. (1978) have obtained a projected view of the H I disk on a plane perpendicular to the major axis as seen from the NE side of the

* Present address: Nobeyama Radio Observatory, Nobeyama, Minamisaku-gun, Nagano 384-13.

galaxy by assuming cylindrical rotation. They found a "perturbed outer arm" in the eastern side, which deviates from the galactic plane by 8 kpc at $R\sim40$ kpc. However, the overall feature of the warping in M31 seems to be not uniquely determined as yet in these works (Newton and Emerson 1977).

In the present paper we make an independent analysis of the H I-line data of Cram et al. (1980) to obtain an overall feature of the warping of the whole disk of M31 by using a similar method to that proposed by Whitehurst et al. (1978).

2. A Model for a Flat Disk with Circular Rotation

For the first step of the analysis, we assume that the H I disk of M31 is flat and infinitesimally thin with circular rotation. If we know the rotation curve of M31, we can calculate the radial velocity v of an arbitrary position on the disk. Figure 1 shows the radial velocity calculated for a model disk plotted against latitude β at two constant longitudes, $\lambda=-36'$ and $-54'$ (solid lines), where (λ, β) are the sky coordinates parallel and perpendicular to the major axis of the disk of M31. In the figure, we superpose observed contour maps of the brightness temperature [$T(\beta, v)$ diagrams] of the H I emission obtained by Cram et al. (1890). To calculate the radial velocity, the following parameters are used: the distance of M31, $d=690$ kpc; the inclination of the disk, $i=77°$; the position angle of the major axis from the north, P.A.$=$ 38°; and the systemic radial velocity, $v_0=-300$ km s^{-1}. The adopted rotation curve is obtained by averaging the northern and southern rotation curves of Paper I. The dashed line in figure 1 indicates the ridge of the observed contour.

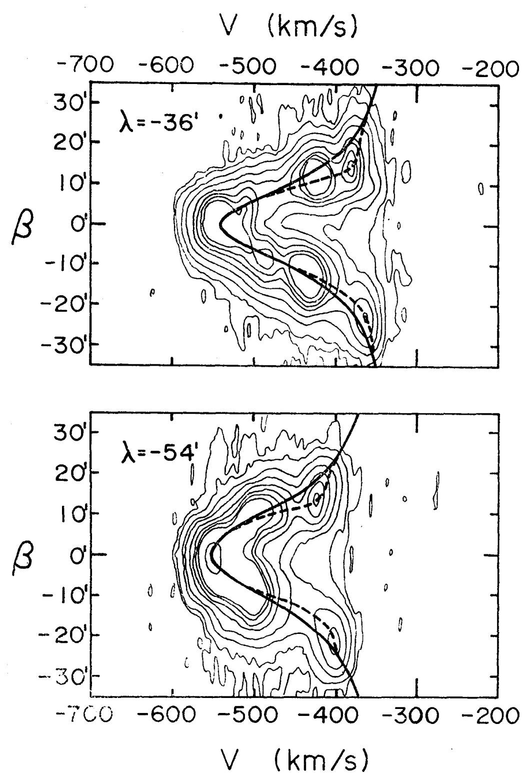

Fig. 1. The solid line indicates the calculated radial velocity of the flat model disk of M31 on the β–v plane. The $T(\beta, v)$ diagrams reproduced from Cram et al. (1980) are superimposed. The dashed line indicates the ridge of the $T(\beta, v)$ diagram.

It is clear that there is a difference between the observed (dashed line) and calculated (solid line) positions of the peak intensity over a considerably wide area of the $T(\beta, v)$ diagrams. There are a number of possibilities for the cause of the difference between the observed and model β–v relations: (1) an incorrect choice of the rotation curve; (2) a deviation of the velocity field from the circular rotation; (3) an incorrect assumption of the inclination of the disk; and (4) the warping of the disk. The rotation curve of M31 is obtained by many authors (see Paper I and references therein) and there are no essential differences among all the rotation curves. The deviation from circular rotation is mainly caused by a perturbation of spiral arms and is of the order of $10\,\mathrm{km\,s^{-1}}$ (Paper II). However, the deviation occurs on a relatively small scale ($\sim$ arm interval) and cannot explain the large-scale discrepancy between the observed and model β–v relations. Thus we may exclude possibilities (1) and (2). Now we can consider the remaining two possibilities, (3) and (4), as the most plausible explanations of the discrepancy between the observed and calculated β–v relations.

Finally we mention the effect of the finite thickness of the H I disk on the $T(\beta, v)$ diagram. A larger thickness (0.4–1.5 kpc) of the H I disk of M31 than that of our Galaxy ($\sim$0.2 kpc) is obtained by Emerson (1976) and Whitehurst et al. (1978). However, if the distribution of the H I gas is smooth as in a Gaussian form in the direction perpendicular to the galactic plane, the effect of the thickness is negligible for the ridge position of $T(\beta, v)$ diagrams, because the maximum position of density located at the center of the disk corresponds to the maximum position of brightness on the $T(\beta, v)$ diagram.

3. Warping of the H I Disk of M31

We estimate the amount of the off-plane displacement of the H I disk over the entire M31. Since the inclined disk can be observed as a warped disk, possibilities (3) and (4) in the previous section can be considered simultaneously. We use the cylindrical coordinates (R, θ, z) in the galactic plane with the origin at the center of M31. The azimuthal angle θ is measured from the negative direction of sky coordinate λ. The z-axis coincides with the rotation axis of M31 and points to the negative direction of β. Under the assumption of a thin and warped disk with cylindrical rotation, the deviation of the disk $h(R, \theta)$ from the "galactic plane" at the position (R, θ) is given by

$$h(R, \theta) = \Delta\beta d \sec i\,, \qquad (1)$$

where $\Delta\beta$ is the latitudinal difference between the model disk and the observed one (the solid line and the dashed line in figure 1) for a constant radial velocity (see figure 2). Here the "galactic plane" is defined as a flat disk with an inclination angle of $i=77°$.

Since the ridge of the $T(\beta, v)$ diagram corresponds to the center of the gas layer for a given longitude, we can estimate the deviation h of the warped disk from the "galactic plane" by using equation (1) and the latitudinal difference $\Delta\beta$. We read the difference $\Delta\beta$ at every 5′ interval of β along the intensity peaks on

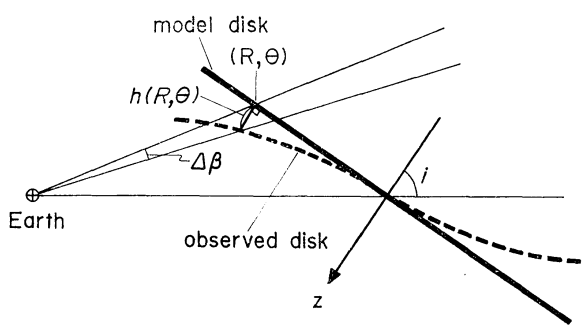

Fig. 2. Schematic relation between the model (flat) disk and observed (warped) disk. The height h of the disk is defined by the deviation of the observed disk from the flat disk.

the $T(\beta, v)$ diagram except for some points where $\Delta\beta$ is not clearly determined. The procedure is applied for all the $T(\beta, v)$ diagrams obtained at 4′.5 interval of λ.

The result is given in figures 3 and 4. Figure 3 shows the radial variation of the "height" $h(R, \theta)$ of the disk plotted on the R-z plane (cross cuts) for various azimuthal angles averaged in sectors at 15° intervals. Figure 4 shows the azimuthal variation of the disk plotted on the θ-z plane for various radii at 5-kpc intervals. The beam width and typical error bars of the determination of h are shown in the figures. The error is due to reading the value of $\Delta\beta$ in the $T(\beta, v)$ diagrams as well as to a finite beam width. We may estimate that the error in position determination by a finite beam is of the order of 1/5 of the beam width, namely $\pm 1'$, which corresponds to ± 200 pc in h. A large deviation from the line of $z=0$ corresponds to a large warping of the disk.

To obtain the average warping of the H I disk, we assume that the disk is composed of many flat rings whose radii are R and $R+dR$. Each ring is located on a plane containing the galactic center. We take 5 kpc as dR and find the best fitted plane for each ring. As a combination of the best-fit flat rings, we find an overall feature of the warped disk. The solid lines in figures 3 and 4 indicate respectively the cross cuts and azimuthal cuts of the best-fit warped disk. Note that the outer part of the eastern (E) side (dashed lines in figures 3 and 4) is obtained by directly using the analyzed points. In figures 3 and 4, we can clearly recognize a warping of the disk. The disk is remarkably warped at $\theta \sim 230°$, while it is relatively flat at $\theta \sim 160°$ and 340°; it means that the node of the warping is at $\theta \sim 160°$. In the outer region the warping becomes larger; at $R \sim$

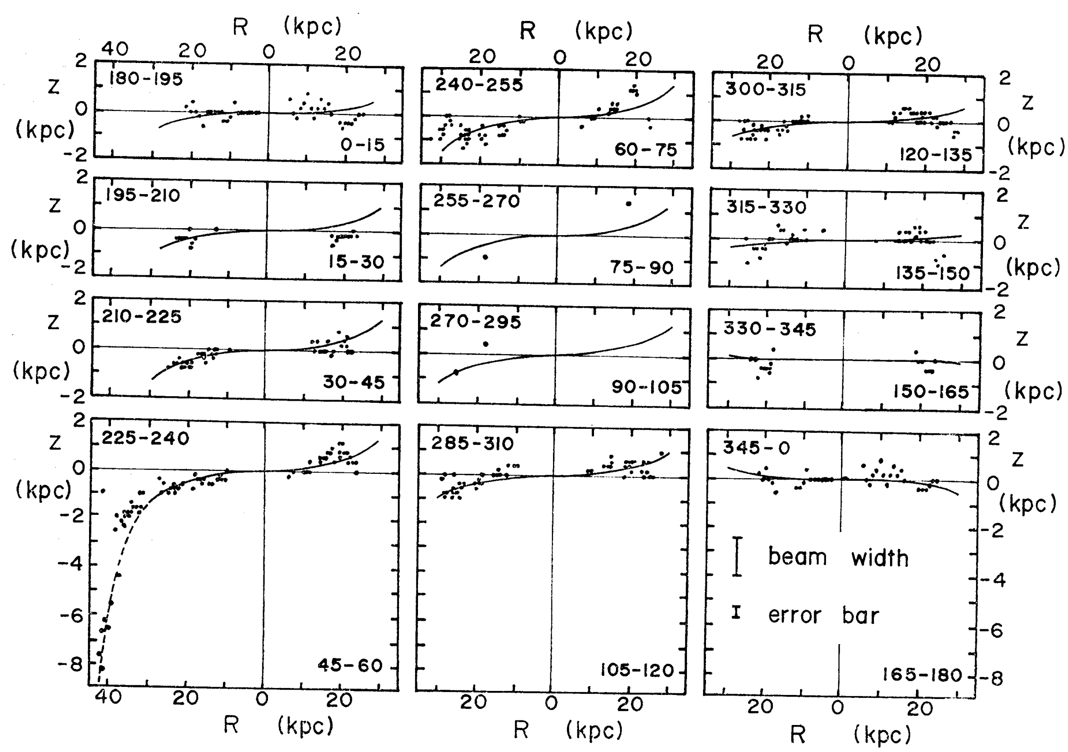

Fig. 3. The radial variation of the height h of the disk plotted on the R-z plane for various azimuthal angles. The numbers in each figure indicate the range of the azimuthal angle. The curved line indicates the best-fit warped disk. The beam width and typical error bars are shown in the last figure.

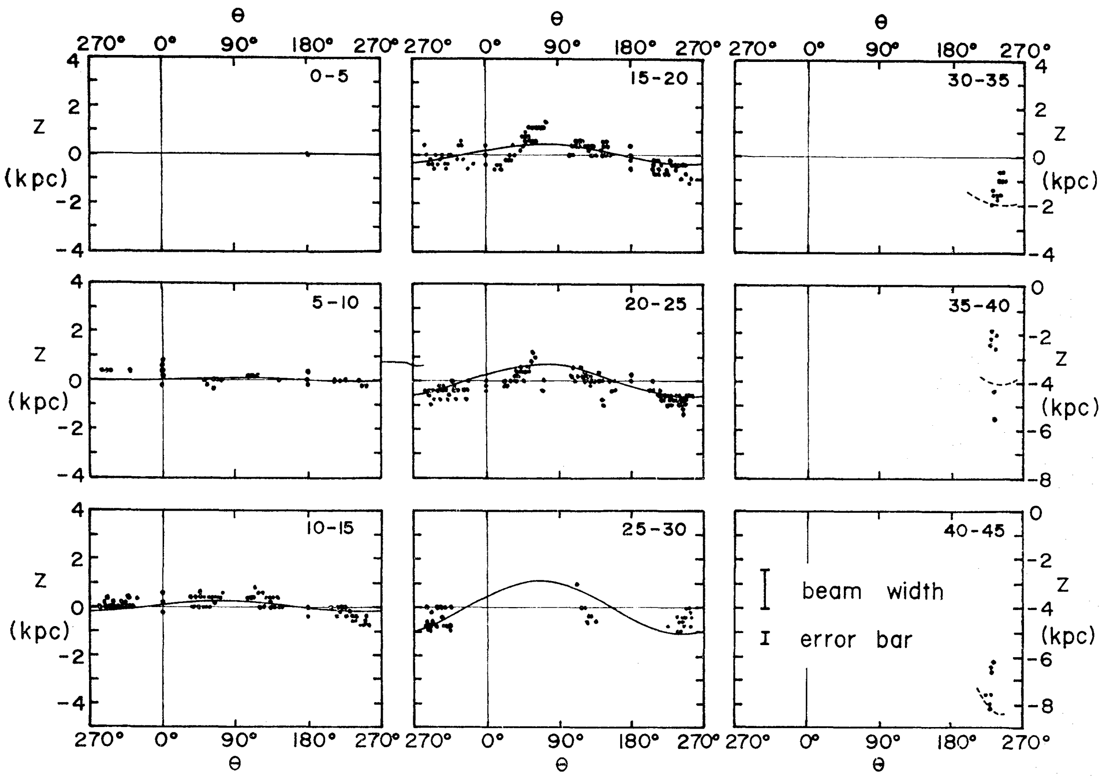

Fig. 4. The azimuthal variation of h plotted on the θ-z plane for various radii. The number in each figure indicates the range of the radius in kiloparsecs. The curved line indicates the best-fit warped disk. The beam width and typical error bars are shown in the last figure.

30 kpc, the warping is as large as 1 kpc. It increases rapidly with R and reaches 8 kpc at $R \sim 40$ kpc along the easternmost arm. This eastern much-warped region corresponds to the "perturbed outer arm" noted by Whitehurst et al. (1978).

If the adopted inclination, $i=77°$, of the "galactic plane" is not correct, the disk should be inclined in figure 3. With this idea, Whitehurst et al. (1978) suggested $i=79°$. However, we cannot estimate the warping in the inner region ($R \leq 10$ kpc) by the present analysis, because the accuracy is poor in this region. It is rather plausible to assume that the inner disk is flat with the inclination of 77°, as the H I disk will coincide with the optical disk in the inner region (see Paper I). We consider here that the deviation of the disk from the "galactic plane," i.e., the warping, occurs in the outer region ($R \geq 10$ kpc).

Figure 5 shows the contour map of $h(R, \theta)$ on the H I disk whose surface density is greater than 10^{19} atoms cm^{-2} (Paper I). The node of the warping is located at $\theta \sim 160°$. Although the surface density of H I gas is less than 10^{19} atoms cm^{-2} at the outer part of E side, the "perturbed outer arm" is clearly recognized in figures 3 and 4. Therefore we think the contour lines are significant, although they are beyond the boundary of the equi-surface density 10^{19} atoms cm^{-2}.

In figure 6, we show a projection on the sky of the rings up to 40 kpc which give the best fits to the plots in figures 3 and 4. The position of the node is indicated by the dashed line. A remarkable appearance of the warping occurs only in the rings of radii $R \geq 35$ kpc. An observable H I disk projected on the sky

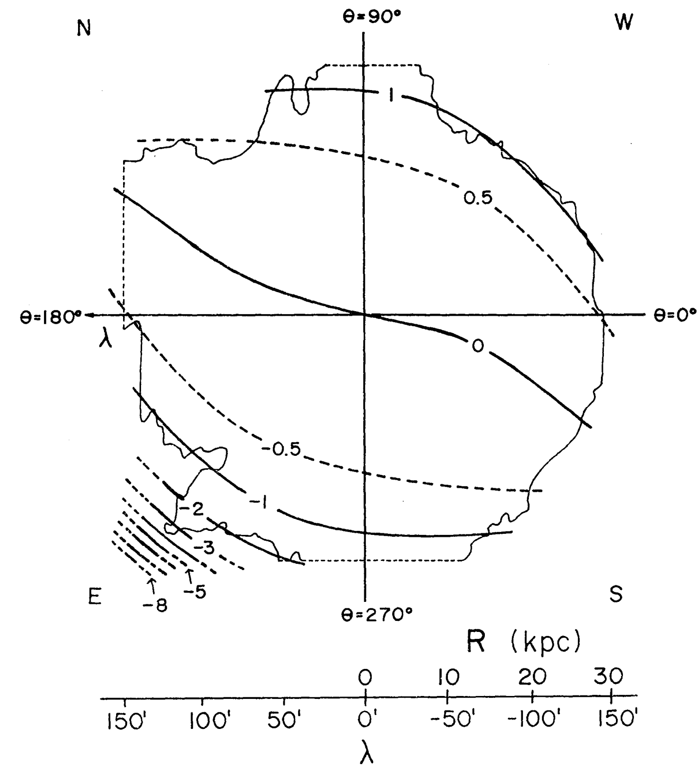

Fig. 5. The equialtitude (h) of the disk plotted on the galactic plane. The thin line encloses the region of surface density greater than 10^{19} atoms cm^{-2}. The altitude h is expressed in kiloparsecs. The outermost E side is recognized as a warped arm where the surface density is less than 10^{19} atoms cm^{-2}.

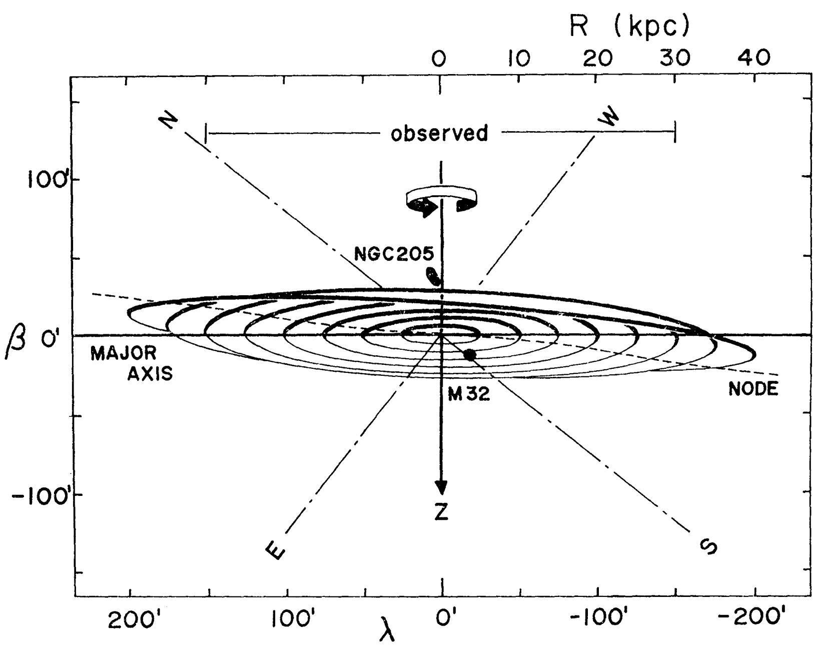

Fig. 6. A projection on the sky of the rings representing the warped disk of M31. The width of each ring is 5 kpc. The nodal line is indicated by a dashed line.

is indicated on these rings in figure 7a, where the disk whose surface H I density perpendicular to the galactic plane is greater than 10^{19} atoms cm^{-2} (the disk in figure 5) is hatched. Since the perturbed eastern far-outer arm is embedded in the inner disk because of its large warping, we show the detailed feature in

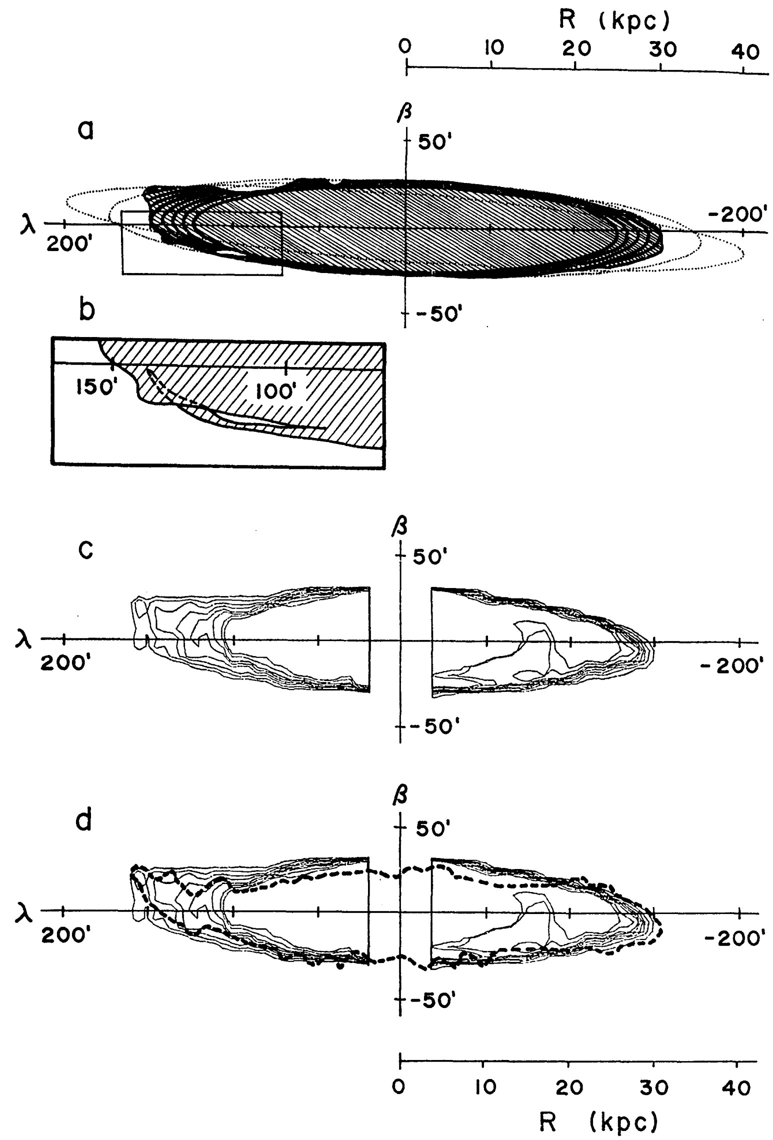

Fig. 7. (a) Observed portions of the warped rings projected on the sky. The hatched region encircled by a thick line represents the outermost contour in figure 5. Unobserved parts of the rings are indicated with dotted lines.

(b) A detail of the "perturbed outer arm." The arm is embedded in the inner disk.

(c) The distribution of the column density of the H I gas on the sky calculated on the basis of our warped disk model using the surface density distribution obtained in Paper I. A finite thickness of the H I gas layer varying with the radius (Emerson 1976) is assumed. The contour lines are for 1, 2, 5, 10, 15, 20, 25, and 30×10^{19} atoms cm^{-2}, respectively.

(d) A comparison with the observation of Newton and Emerson (1977) (dashed line).

figure 7b. Figure 7c shows the distribution of the column density of the H I gas on the sky calculated by combining the H I gas distribution obtained in Paper I, our warped disk model and the finite thickness of the H I disk obtained by Emerson (1976) which increases with the radius. To compare our model with observations, we superimpose the observed H I disk reproduced from Newton and Emerson (1977) (dashed line) on the distribution of the column density in figure 7d. Our result shows a good coincidence with their observation.

4. Discussion

We obtained an overall feature of the warping of the H I disk of M31 by using the differences between the observed and calculated β–v relations. The present analysis is based on an assumption of cylindrical rotation. We note that the position of the "perturbed outer arm" in the E side and the amount of its warping are less certain compared with those of the other regions, since departures from the circular rotation may become larger in this region. However, the overall feature of the warping obtained here is essentially unchanged.

Our result is consistent with the results of Newton and Emerson (1977) (see figure 7), although the variation in position angle with radius in our result (figure 6) is a little smaller than those obtained by Newton and Emerson (1977): We have found the inclination of the ring, $i=84°$, and the position angle, P.A.$=34°$ at $R=40$ kpc, while $i=80°$ and P.A.$=37°$ at $R=30$ kpc.

The displacement of the H I disk of our Galaxy from the galactic plane is about a few hundred parsecs in the region of the Perseus arm and amounts to a few kiloparsecs at galactocentric distances of 10–20 kpc at $l\sim50°$–$150°$ (e.g., Davies 1972; Verschuur 1973). The warping of M31 is, therefore, smaller than that of our Galaxy in the region of $R<30$ kpc. However, the behavior of the "perturbed outer arm" at $R\sim30$–40 kpc in the E side is very peculiar and the H I disk deviates 2.5 kpc from the galactic plane at $R\sim35$ kpc and reaches 8 kpc at $R\sim40$ kpc. The corresponding feature to this arm is not found in the W side. This fact indicates that the warping is asymmetric. An asymmetric warping, although in an inner region at $R\sim10$ kpc, is suggested by Unwin (1980) from his interferometric observations.

Byrd (1978) examined the tidal interaction of M31 with the companion galaxy M32. However, the disk is disturbed only in the inner region (typically $R<20$ kpc) in his calculation. The tidal interaction with M32 must not be sufficient to deviate the warped outer arm considered here. Other possible tidal disturbers are the companion galaxy NGC 205 and the nearby galaxy M33. However, we might note that there are several warped galaxies such as NGC 4665 and 5907 which have no companions (Sancisi 1976). It is, therefore, not clear whether the origin of the warping of H I disk of M31 is due to tidal distortion.

The present work was in part supported by the Scientific Research Fund of the Ministry of Education, Science, and Culture under Grant No. 574096 (T. Sawa in FY 1980), No. 740107 (T. Sawa in FY 1981), and No. 542003 (Y. Sofue in FY 1980 and 1981). Numerical computations were made on the FACOM M190/200 at the Institute of Plasma Physics, Nagoya University.

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