WARPING AND THICKNESS OF GALACTIC GAS LAYERS

Hugo van Woerden
Kapteyn Astronomical Institute, University of Groningen,
Groningen, The Netherlands

Summary The evidence for warps in the gas layers of galaxies is reviewed. Both the 21-cm line intensity distribution on the sky in edge-on systems and the hydrogen velocity fields in other systems indicate that warped gas layers are common, more common than close companions. Hence, warps probably persist for several times 10^9 years.

The thickness of the gas layer in NGC 891 appears to increase outward, similarly to that in our Galaxy.

INTRODUCTION

The standard model for spiral and lenticular galaxies consists of a spheroidal bulge and a thin, flat disk. The model can, of course, best be tested in galaxies where the disk is seen "edge-on". Among 15-20 such galaxies in the Hubble Atlas, most have an undisturbed, flat disk; NGC 5866 has a slightly (2°) tilted inner dust lane; and only in one, the lenticular galaxy NGC 4762 (Hubble Atlas, page 8), do deep exposures show the outermost parts of its wafer-thin disk to be warped, and probably even corrugated. Arp's Atlas of Peculiar Galaxies illustrates more deviations from flatness, and Arp (1964) noted a 5° bending in the plane of the Andromeda Nebula; but to the optical observer warped disks remain an exception.

THE WARP IN OUR GALAXY

The early surveys of neutral hydrogen in our Galaxy (Muller and Westerhout, 1957; Westerhout, 1957; Schmidt, 1957; Kerr, Hindman and Gum, 1959; Oort, Kerr and Westerhout, 1958) demonstrated that the gas layer is very flat indeed in the inner parts of the system: inside the solar circle, deviations of the midplane from a flat "principal plane" did not exceed 100 pc. At greater distances from the centre, however, the gas layer proved to curl away from the principal plane (Burke 1957, Kerr 1957) up to heights $|z| \sim 1000$ pc (Oort et al., 1958) at $R \sim 16$ kpc*, in a symmetric, integral-sign (or "hat-brim") pattern. Much greater deviations, of several

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* All heights and distances in this section have been recalibrated to a sun-centre distance, $R_o = 10$ kpc.

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 501 510.

kpc, were later reported at greater R by Kepner (1970), Davies (1972) and Verschuur (1973), cf. also Habing (1966).

Several attempts were made to explain this warp. Burke (1957), Kerr (1957) and many others estimated the tidal effects exerted by the Magellanic Clouds, but only Hunter and Toomre (1969) succeeded in showing that these galactic satellites might indeed have caused the warp in the gas layer on a recent, close passage. The intergalactic-wind model by Kahn and Woltjer (1959) and the free-precession model by Lynden-Bell (1965) did not require the influence of such companions. Whether or not the galactic warp was peculiar, remained an Open question.

OTHER GALAXIES

Some fifteen years later, Gordon (1971) and Wright, Warner and Baldwin (1972) observed anomalous features in the distribution and velocity field of HI in Messier 33. They noted that these features could be explained by a warped gas layer; however, both the required amplitude (∿6 kpc) of the warp and the great distance (∿150 kpc) of the nearest neighbour, Messier 31, caused these authors to wrap this suggestion in considerable hesitation.

Several years passed before Rogstad, Lockhart and Wright (1974) showed convincingly that the pronounced asymmetries in the gas distribution and velocity field of Messier 83 could be well represented by a set of concentric rings, progressively inclined with respect to the main plane of the galaxy (Figure 1). This suggested strongly that the gas layer in this galaxy was severely warped (by about 30°). Subsequently, the same authors (Rogstad, Wright and Lockhart, 1976) represented Messier 33 by a similar model. In either case, Rogstad et al. agreed that neither a tidal nor a primordial origin of the warp seemed likely, and they wondered whether recent infall of gas might be responsible.

EDGE-ON GALAXIES

The nearest edge-on systems are an obvious place to look for phenomena similar to those in our Galaxy. As soon as Westerbork had a line receiver

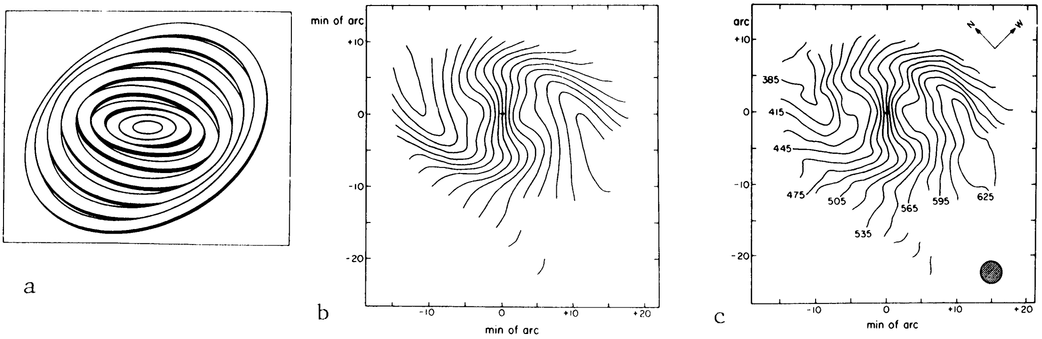

Figure 1. The warp in M83 (Rogstad, Lockhart and Wright, 1974). (a) Tilted-ring model. (b) Model velocity field. (c) Observed velocity field.

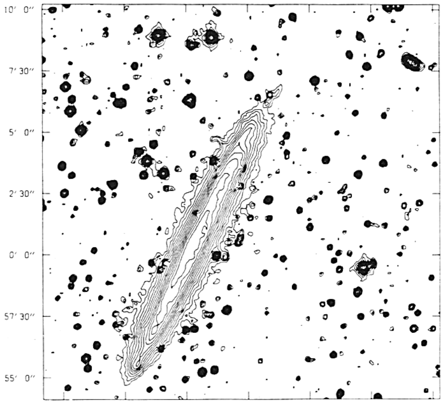

Figure 2. Isophote map made from two deep IIIa-J plates of NGC 5907 taken by Van der Kruit and Bosma with the 48-inch Palomar-Schmidt telescope (Van der Kruit, 1978). Contour values range down from 27.5 mag arcsec^{-2} in steps of 0.5 and are accurate to ±0.2. Note flatness of disk out to faintest contour.

(1971), Sancisi and Allen observed NGC 891. The gas layer in this system turned out to be perfectly flat (Sancisi, Allen and Van Albada, 1975), in keeping with the lack of a companion.

The next object observed, NGC 5907, however, turned out to have a very strong warp (Guélin et al., 1975; Sancisi, 1976). By now, of the five edge-on galaxies studied (Table 1), four are warped. One of these, NGC 4631, is surrounded by a complex distribution of neutral hydrogen (Weliachew et al., 1978); this galaxy has two near companions, and indeed Combes (1978) has shown that the distribution and kinematics of the gas around NGC 4631 can be fairly well represented by a tidal-interaction model. For the other three warped galaxies, the nearest major neighbour is at a projected distance of six or more De Vaucouleurs diameters; this implies that either 1) the relative velocity is strongly hyperbolic, hence any interaction would have been brief and inefficient; or 2) any close encounter would have occurred several times 10^9 years ago - too long (Hunter and Toomre, 1969) for a warp to maintain its organized shape. The statistics suggest that warps are not induced by major, nearby companions but have some other cause, and/or that they must be able to survive much longer than we think. Tubbs and Sanders (1978) now appear to have found a mechanism that allows warps to persist for long.

Published photographs suggest that the warps in the neutral hydrogen mainly occur in regions outside the optical disk. Isophotometry on deep IIIa-J plates of three edge-ons by Van der Kruit (1978) confirms this, and further shows (cf. Figure 2): a) the optical disks remain flat out to an (edge-on!) brightness level as low as J = 27 mag arcsec^{-2}; b) the intensity gradient over the last three magnitudes is very steep. This indicates that the warps probably occur in regions of quite low mass density, in agreement with the suggestions by Tubbs and Sanders (1978).

"KINEMATIC WARPS"

In his recent thesis, Bosma (1978) has compiled detailed HI velocity fields (Figure 3) for about 20 galaxies, from measurements made at Westerbork and (by others) at several other observatories. In most of these galaxies, Bosma finds evidence for large-scale deviations from axial symmetry in the distribution and motions of the gas. In a number of galaxies (notably: M31, M33, M83, and NGC 300, 2805, 2841, 5033, 5055 and 7331) these deviations are well represented by a tilted-ring model similar to that (cf. Figure 1) first proposed by Rogstad et al. (1974) for M83; the orientation of the rings varies progressively outward, but all rings are presumed to be in circular motion about the centre. Bosma has also developed tilted-ring models for the warped edge-on galaxies discussed in the previous section.

The success of these tilted-ring models suggests that all of the galaxies mentioned in the preceding paragraph have warped gas disks. Bosma calls these "kinematic warps". The high frequency of kinematic warps

TABLE I

Warps in edge-on galaxies

Name	Relative resolution: θ/D_o (a)	Warp?	z/R (max.) (b)	Nearest major companion: distance/D_o (c)	Notes and references
Milky Way	<0.02-0.002	yes	∿0.05	∿2	
NGC 891	0.045	no	<0.03	>20	(e)
NGC 4244	0.10	yes	0.05	8.5	(f)
NGC 4565	0.11	yes	∿0.12	6.1	(f)
NGC 4631	0.14	yes	0.10	3.0	(d) (g)
NGC 5907	0.11	yes	0.2	8.0	(f) (h)

Notes

(a) θ = beamwidth perpendicular to galactic plane;
D_o = De Vaucouleurs diameter, from Second Reference Catalogue.
(b) Highest value of z, height of warp above principal plane, relative to distance R from galaxy centre.
(c) "Major companion" ≡ magnitude difference <2. Velocities (Second Reference Catalogue) taken into consideration.
(d) Elliptical companion, $\Delta m \sim 4$, at 0.2 D_o. Tidal interaction with both companions, see Combes (1978).

References for warp data: (e) Sancisi and Allen (1978), (f) Sancisi (1976), (g) Weliachew, Sancisi and Guélin (1978), (h) Sancisi (1977).

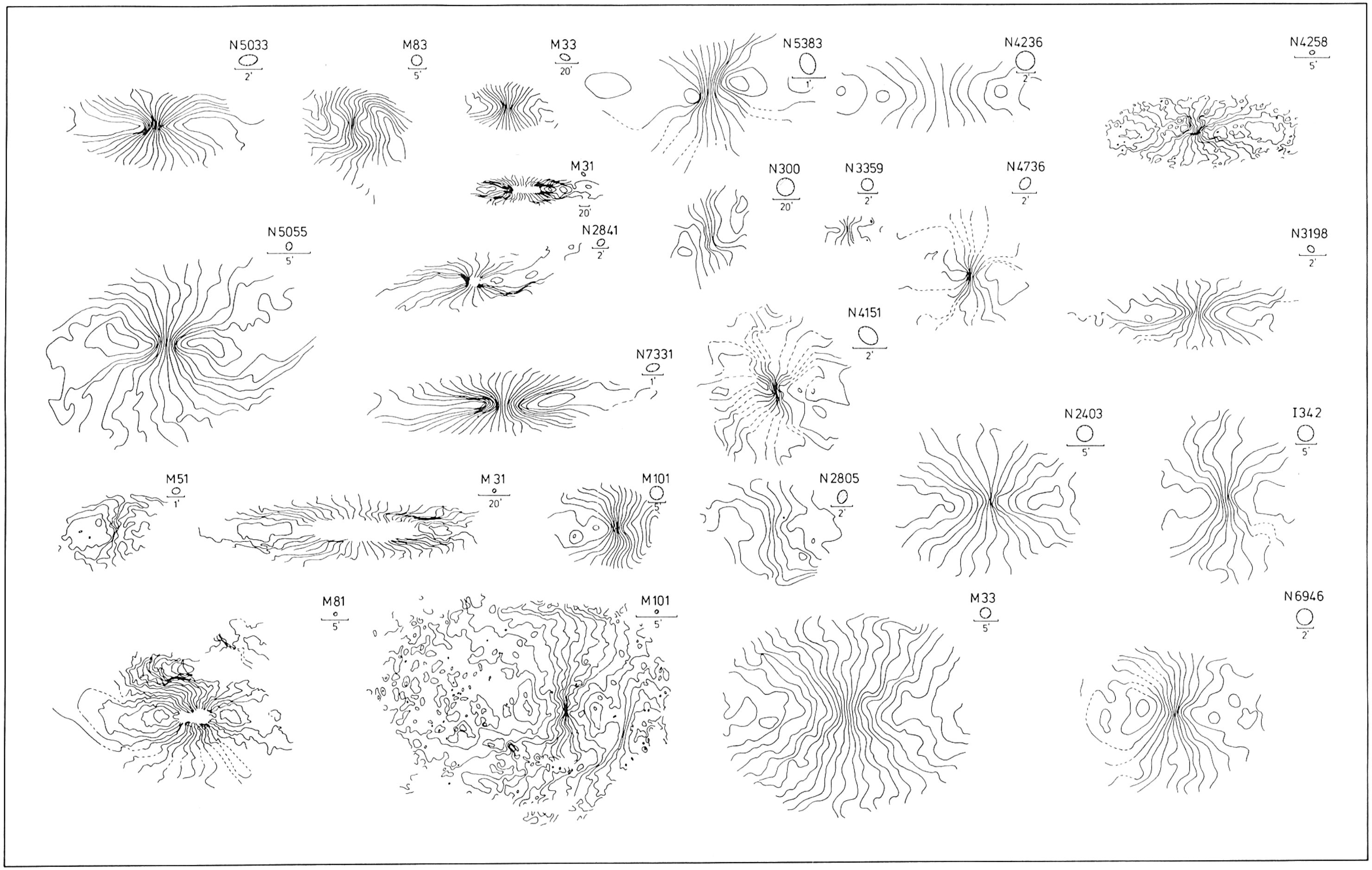

Figure 3. Velocity fields of 22 spiral galaxies, from high-resolution studies by various observers (Bosma 1978). Note the frequent, strong deviations from axial symmetry.

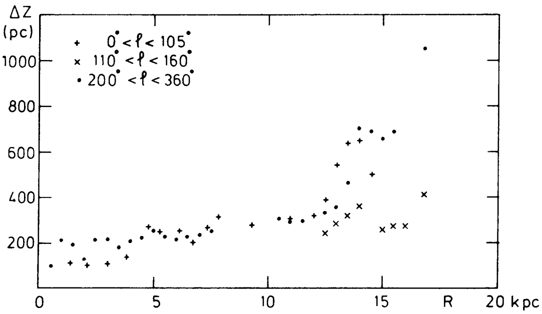

Figure 4. Layer thickness Δz (between half-maximum-density points) of neutral hydrogen in our Galaxy, plotted as function of distance R from the centre. Data taken from Jackson and Kellmann (1974, Tables 1-5): plus signs, regions with $0^{o} < \ell < 180^{o}$; circles, regions with $180^{o} < \ell < 360^{o}$.

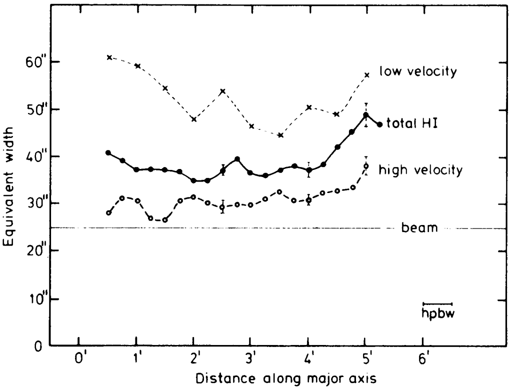

Figure 5. Equivalent width of intensity distribution observed across major axis for neutral hydrogen in NGC 891 (Sancisi and Allen 1978). Separate curves plotted for "high" and for "low" velocities (see text).

supports and amplifies the findings of the previous section. The general conclusion appears justified that warped gas disks are common among galaxies.

THICKNESS OF GAS DISKS

For the thickness of the gas layer in our Galaxy, Schmidt (1957) found Δz ∿ 270 pc between points of half-maximum density at 4 < R < 8 kpc. (Again, we recalibrate thicknesses and distances to a sun-centre distance R_o = 10 kpc.) The thickness varied hardly with R, although the force K_z perpendicular to the plane was estimated to vary by an order of magnitude over this range. The near-constancy of Δz in the annulus 4 to 8 kpc temporarily led to the belief that the thickness was similar throughout the Galaxy (Oort, 1959) except in the central region where it decreases to about 100 pc (Rougoor and Oort, 1960). In the outer parts, Lozinskaya and Kardashev (1963) found the layer thickness to increase strongly, to Δz ∿ 1000 - 2000 pc at R ∿ 15 - 20 kpc. Values Δz ∿ 700 pc at R ∿ 15 kpc were reported by Van Woerden (1967) and by Kerr (1969). A new study by Jackson and Kellmann (1974), based on high-resolution surveys, confirmed the earlier findings: Δz ≈ 250 pc, and almost constant, at 4.5 < R < 10 kpc; Δz ∿ 100 - 200 pc at R < 4 kpc, and ∿600 pc at R < 14 kpc. Figure 4 is a plot of the layer thicknesses tabulated by Jackson and Kellmann. On the whole, Δz appears to rise gradually with R, with a steep increase beyond R = 12 kpc.

Little is known for other galaxies. The 1-arcmin resolution used for most objects listed in Table 1 corresponds to several kpc in most cases! The only edge-on galaxy sofar observed with 0!5 resolution is NGC 891;

for a Hubble constant of 100 km s^{-1} Mpc^{-1}, this corresponds to 1 kpc. The analysis of the observations (Sancisi and Allen, 1978) is difficult: the observed intensity distribution across the major axis is influenced by 1) the z-distribution (and layer thickness) of the gas, 2) the inclination (and possible warping) of the gas layer to the line of sight, 3) optical-depth effects, 4) beam broadening. Only the last effect is accurately known. Figure 5 shows the equivalent width W(y) of the intensity distribution across the major axis, as a function of position x along the major axis. Separate curves are given for gas with "high" and with "low" velocity. Gas located close to the line of nodes (of galactic plane and sky plane) will be observed with its full rotational velocity; gas far from the line of nodes has a much smaller rotation component in the line of sight. The equivalent width W(y) of the "high-velocity" gas is little affected by the inclination; hence the run of W(y) with x suggests that the layer thickness does increase with radius R. This conclusion is strengthened by the fact that optical depth will raise W(y) for small x.

Sancisi and Allen place a lower limit $i > 87\overset{\circ}{.}5$ on the inclination, from a comparison of the intensity distributions I(y) and I(x) along minor and major axes. From an analysis of I(y) they then conclude that the layer thickness is unresolved, hence $\zeta < 15'' \sim 0.5$ kpc at radii $R < 2' = 4$ kpc; for R between 5' and 6' (10 and 12 kpc), $\zeta \sim 0.5 - 1$ kpc. These results, though necessarily rough, appear in good agreement with those for our own Galaxy; Sancisi and Allen show that also the hydrogen size and distribution, hydrogen mass, total mass and rotation velocity are all quite similar in both galaxies.

WHAT NEXT?

Further work on disk thicknesses will clearly require observations at $0\overset{'}{.}5$ resolution (or better), and improved sensitivity. For a better understanding of the dynamics, origin and evolution of warps, highly sensitive observations at high resolution will have to provide extended rotation curves and detailed gas distributions in the far outer parts of edge-on galaxies.

ACKNOWLEDGEMENTS

I thank A. Bosma and P.C. van der Kruit for the use of unpublished information. In particular, I am grateful to Renzo Sancisi for several discussions. The Westerbork Radio Observatory is operated by the Netherlands Foundation for Radio Astronomy, with financial support from ZWO.

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DISCUSSION

Verschuur: Based on my measurements of the warp in our Galaxy, I produced a model cross-section for the Galaxy which when overlaid on the HI map for NGC 5907 gives an excellent fit. I reassert that the evidence for a warp of the order of 5 kpc in the Galaxy is very strong, especially in the second quadrant of galactic longitude.

van Woerden: I agree that our Galaxy may be warped up to 5 kpc. Habing (1966, BAN 18) already showed that the outer arms have asymmetric z-distributions reaching up to 3-5 kpc. However, it is not clear that the column densities of hydrogen in these features are comparable to those found by Sancisi in NGC 5907. Our opinions may diverge in the interpretation of the "high-velocity clouds".

Sanders: Concerning the kinematic warps, such as exemplified by M83 or the various cases cited by Bosma: Is it the case that these warps lie outside of the optical disk?

van Woerden: Bosma's tilted rings generally start outside the Holmberg radius.

de Vaucouleurs: NGC 5907 probably provides a better comparison to our Galaxy than NGC 891 which is type Sb (larger bulge/disk ratio). We have recently completed photometry of NGC 4631. It has an extensive thick disk with an exponential z-distribution on a scale roughly similar to the so-called radio "halo".

Pişmiş: Only in the case of an edge-on Galaxy can one be sure of the existence or not of a warp. I showed by geometrical considerations in 1966 that if spiral arms are not logarithmic spirals the projected major axis will show a warp.

van Woerden: It is clear that the case for warped disks can only be unambiguously proven in edge-on galaxies. In inclined galaxies, any distorted observed velocity field may be represented by a planar distribution of gas together with an appropriate arrangement of non-circular motions. However, in his thesis Bosma shows convincingly that a tilted-ring model à la Rogstad gives a good fit to many galaxies with distorted outer velocity fields, as well as to the warped edge-on galaxies. This suggests that warps are indeed a frequent, if not general, phenomenon.

Burstein: In Bosma's figure depicting the HI rotation curves of spirals, it appeared that the "kinematical warp" in M31 extends to the center of the galaxy, and is continuous throughout the disk of M31. Does this imply a difference in the kinematics of the gas and the stars in M31?

van Woerden: I am not sure that the kinematical warp continues so far in. However, note that a similar phenomenon ("twist") in the velocity field may be caused by an elongated inner structure (bar or oval). Bosma finds evidence for such oval distinctions in many galaxies.

Burstein: In my recent photometric study of S0 galaxies, I discovered that the brightness distribution in edge-on S0's requires the presence of a third, separate luminosity component, termed a "thick disk", in addition to a thin disk and a spheroid. I searched for the presence of a "thick disk" in spirals, and did not find any evidence of thick disks (as found in S0's) in six spirals, including M31. One can take the major axis profile of M31, assume the disk is thin (a/b $\gtrsim$ 40:1) and axisymmetric, and fit the light distribution (from de Vaucouleurs) perpendicular to the major axis. The thin disk approximation fits the observed light distribution (termed a perpendicular profile) to 27 mag arcsec^{-2} B. Thus, the stellar distribution is not warped to this surface brightness.

Toomre: Could you please summarize again just how far we have gotten with attempts to observe optical counterparts to the HI warps seen in edge-on galaxies like NGC 5907 and 4565?

van Woerden: Van der Kruit has taken deep IIIa-J plates of NGC 5907, 4565, and 4244. Isophotometry of these plates down to 27.5 mag arcsec^{-2} shows no warps within the Holmberg radii (26.5 mag arcsec^{-2}), and only a faint hint of a warp in the outermost contours of one or two of these galaxies.

Burton: In our own Galaxy, doesn't the warp occur outside of the "optical disk"?

van Woerden: Not quite. Our warp starts just outside the solar circle. The Perseus arm is at $z \approx + 0.2$ kpc, and is rich in associations (though HII regions are locally lacking). The Holmberg radius was estimated at 17 kpc earlier in this Symposium. Remember, however, that a warp of 0.2 kpc is very small compared to those measured at Westerbork in other galaxies.

Lequeux: Guibert, Viallefond and I have just made the sort of search for a warp in the young population in the Galaxy that Dr. Burton was mentioning. The results are inconclusive (Astron. & Astrophys., in press).

Kerr: There is some evidence that stars are to be found in the warp of our Galaxy. Graham was one of the first to show this. A search for such objects is an important problem for optical observers.

van Woerden: I could certainly not claim that warped gas cannot form stars.

Jackson: In our work on distant HII regions, we find that the most distant ones, 7 to 8 kpc from us and in the directions near $\ell = 150°$ and 240° show a departure from the plane which is in the same direction but less than the maximum departure in the 21-cm data (i.e., above the plane near $\ell = 150°$ and below it near $\ell = 240°$).

van Woerden: The presence of such stars, of course, implies that star formation occurs in the warped disk. It does not imply that our Galaxy has a warped optical disk brighter than 27 mag arcsec^{-2}, say.