

HI VELOCITY FIELDS AND ROTATION CURVES

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ABSTRACT

Recent results on 21-cm line velocity fields of spiral galaxies are reviewed. Attention is drawn to the sometimes discrepant results on the spatial orientation of galaxies inferred from various methods. Major classes of deviations from circular, planar, motion of the neutral gas are discussed. Some comments are made about HI rotation curves.

I. INTRODUCTION

HI velocity fields are now available for several tens of spiral galaxies. Most of these data come from aperture synthesis studies in the 21-cm line, and, because of the two dimensional mapping involved, much more information becomes available about a galaxy than just its axisymmetric rotation curve. Moreover, the HI usually extends to the outer parts, and often beyond the optical image so that rotation data are known at larger distances from the centre than be obtained by optical spectroscopy. However, the relative angular resolution (ratio of beamsize to diameter of the galaxy) is in most cases rather low (~ 0.02 to 0.2) so that resolution effects play a significant role in the interpretation of the raw data.

As a starting point for the discussion let me review the results of a comparative study of about 20 galaxies with detailed HI data obtained in the 1970's and published recently (Bosma, 1981b). Based on the velocity fields from a variety of sources the following conclusions were arrived at:

1. Many spiral galaxies have large scale deviations from axial symmetry. Four categories of distinctive signatures in the velocity fields can be recognized: a) spiral arm motions, b) bars and oval distortions, c) warps, and d) asymmetries.
2. Rotation curves are fairly flat out to large radii. For those galaxies with both photometry and kinematical data available one can

make estimates of the local mass-to-light ratio, which is found to increase with increasing radius (cf. Bosma and Van der Kruit, 1979). The HI extent of a galaxy is not very predictable: in some cases large HI envelopes are found, while in other cases the HI is confined to the optical image.

3. From HI data alone it is difficult to find a dynamical basis for Hubble types. This is partly due to lack of angular resolution in the central parts of galaxies and partly because HI has not been detected in the central parts of some early type galaxies with large bulges.

II. ORIENTATION PARAMETERS

Before discussing some of the intrinsic properties of spiral galaxies one has to know the orientation of the galaxy in space. There are several ways of determining the orientation parameters, but all assume that the disk of a spiral galaxy is circular and planar at a certain range of radii so that we need to know only the position angle of the line of nodes, pa , and the inclination angle, i . These methods are:

- photometrically, from the orientation of the major axis and the ratio of major to minor axis diameter at a given isophote, e.g. the 25th magn arcsec⁻², or from isophotal maps obtained in detailed surface photometry studies.
- kinematically, by assuming circular motion and solving for pa and i on the basis of observed radial velocities from either long slit spectra or from two dimensional mapping with a Fabry-Perot interferometer or with HI line synthesis.
- spiral rectification, assuming usually that spiral arms have a logarithmic form. This method goes back to Von der Pahlen (1911) and was extensively used by Danver (1942). Recently, Fourier analysis of the spiral pattern in e.g. HII regions has attracted some interest and also yields orientation parameters (e.g. Considère and Athanassoula, 1982). This method is qualitatively related to Danver's method.

If all is well with a spiral galaxy the various methods will yield the same orientation parameters. If this is not the case it might be due to several causes like the presence of a bar or oval distortion in the disk, a strong asymmetry, or the spiral pattern might not be in the form assumed to do the rectification.

I have compared the results for the orientation parameters obtained from HI data with those from spiral rectification. Though there is general agreement I will call attention to two galaxies for which there is clear disagreement between the various methods.

a. NGC 4321. The outer spiral arms of this bright Virgo cluster spiral outline a relatively face-on disk in position angle $\sim 15^\circ$ (see e.g. Sandage, 1972). Kinematics of the nuclear region by Van der Kruit (1973) shows a pa of $\sim 117^\circ$, while Rubin et al. (1980) found for the main body $pa \sim 155^\circ \pm 20^\circ$, a value confirmed by a recent HI study

using Westerbork by Warmels (1982). Anderson, Hodge and Kennicutt (1982) find from rectification of the principal spiral arms $pa \sim 108^\circ$. This galaxy most likely has a fat bar which might account for some of the misalignments indicated by the disagreements between the various estimates of the position angle of the major axis.

b. M33. The photometric study by De Vaucouleurs (1959) gives $pa = 23^\circ \pm 2$ and $i = 55^\circ \pm 2$. These orientation parameters are corroborated by the HI synthesis studies of Warner et al. (1973), Rogstad et al. (1976) and Newton (1980a). However, Danver (1942) found for the two principal arms $pa = 49^\circ$ and $i = 40^\circ$. This discrepancy prompted Sandage and Humphries (1980) to reexamine the spiral structure of this galaxy. They delineate 5 pairs of arms; the inner two at the orientation found by Danver and the others with pa of order 15° and i of order 65° . They then suggest that the optical disk of M33 must be severely warped in order to produce such an arrangement. This warping continues smoothly outside the optical disk in the HI plane, where it is inferred from the kinematics as discussed by Rogstad et al. (1976) and Reakes and Newton (1978). Yet it is difficult to see why there is no kinematic signature of the warp in the optical part of M33. None of the above mentioned HI studies have found substantial deviations from axial symmetry there even at the level of 5-10 km/sec. However, the warp proposed by Sandage and Humphries should show clearly its signature in a kinematical major axis which changes its position angle as function of radius in the optical parts of the disk. Since this is not seen I think that the assumption underlying the rectification, i.e. that the arms are described by a logarithmic spiral,

Table 1. Orientation parameters, comparison between Danver & HI results.

Galaxy NGC	Danver's results		HI results		(ref)	Δpa (corrected for winding)
	pa	i	pa	i		
300	111.5	39.8	108	55	1	3.5
598	48.9	40.4	23	55	2	-25.9
628	0.4	34.9	15	--	3	14.6
2403	125.0	54.5	125.5	60	4	0.5
2841	147.8	64.0	148	68	5	- 0.2
3031	153.6	59.2	149	59	6	4.6
3198	41.8	72.7	36	70	5	5.8
5033	166.6	58.5	172	63	5	- 5.4
5055	98.9	58.6	98	55	5	0.9
5194	41.7	35.2	- 8	20	7	49.7
6946	52.2	31.1	62	30	8	9.8
7331	165.4	69.1	167	75	5	1.6

references for HI data. 1. Rogstad et al. (1979), 2. Rogstad et al. (1976), 3. Briggs (1982), 4. Shostak (1973), 5. Bosma (1978, 1981a), 6. Visser (1978), 7. Tully (1974), 8. Rogstad et al. (1973).

is incorrect.

In most cases though there is relatively good agreement between the orientation parameters determined by Danver (1942) and those from HI velocity fields, as is shown in table 1 for a dozen galaxies. Most of that table is self explanatory, only in the last column it should be noted that the difference is always taken in the same sense with respect to the winding pattern of the spiral arms. The outstanding deviators are M33, NGC 628, and M51, all very interesting galaxies in their own right.

III. SPIRAL STRUCTURE, ASYMMETRIES

Only for a few galaxies the angular resolution at 21 cm is good enough to enable a detailed study of the motions associated with the spiral arms. The best known case is M81, where the observations by Rots and Shane (1975) show a regular pattern of wiggles, which has been reproduced by Visser (1978) in the context of the Lin-Shu-Roberts density wave theory. Such wiggles are indeed associated with the change in velocity of the gas as it passes through the spiral arm shock region and can be reproduced also by other density wave theories (cf. Toomre, 1981).

There are several hints of these wiggles in other galaxies, but in the best studied cases, M31 and M33, there are no clear patterns as in M81, either because it is not there (in M33, cf. Newton, 1980a) or because the pattern is not due to a simple 2-arm spiral (in M31, see contribution by Brinks in this volume).

It may be expected that the new generation of Fabry-Perot interferometers like TAURUS or the French system will generate a number of pictures in which these motions can be recognized. The preliminary results from TAURUS on NGC 2997 and M83 presented by Atherton and Allen at this meeting are very suggestive in this respect. Note that the axisymmetric rotation curve cannot be derived directly from the mean circular velocity in annuli if strong spiral arm perturbations are present, but that a correction is necessary (cf. Visser, 1978).

Asymmetries occur in nearly every galaxy and it is useful to distinguish several categories:

- HI intensity asymmetries. It occurs very often that one side of a galaxy is stronger in HI intensity (sometimes up to 50% in the arms) than the other side, e.g. M81 inside 12 kpc (Rots and Shane, 1975) and NGC 3198 (Bosma, 1981a).
- Optical asymmetries in the inner parts. Galaxies like M33, NGC 1313 and NGC 4027 are asymmetrical in the central parts in that the nucleus, or the bar in the magellanic barred spirals, is displaced from the centre of the disk. Dynamical models have been constructed for these situations (e.g. Colin and Athanassoula, this volume);

alternatively it has been suggested that stochastic self propagating star formation can also account for the appearance of asymmetries in magellanic systems (cf. Feitzinger et al., 1981).

- Optical asymmetries in the outer parts. Some giant galaxies like M101 show a distinct asymmetry, predominantly in the outer parts. In both M101 and NGC 2805 the HII regions are more dominant on one side of the galaxy and the HI on the other side (cf. Bosma et al., 1980). The velocity field of M101 is very distorted in an asymmetric manner (Rogstad and Shostak, 1971; Bosma et al., 1981).

- HI distribution asymmetries in the outer parts. Sometimes the detectable HI extends very far out at only one side of a galaxy, e.g. in IC342 (Newton, 1980b) or NGC 891 (Sancisi and Allen, 1979); sometimes there are only moderate differences in HI extent and a single extended cloud seems to be responsible for the asymmetry, e.g. NGC 2841 and NGC 5033 (Bosma, 1981a).

Baldwin et al. (1980) reviewed the last two asymmetries and argue that these $m = 1$ distortions can be relatively long lived since $\kappa - \Omega$ does not vary all that much in the outer parts of the disk. Note that asymmetries do hamper the determination of accurate rotation curves in the asymmetric parts of a galaxy, and it is not at all obvious to include the outer points in e.g. NGC 891 in a rotation curve analysis since a large amount of non-circular motion could be present there.

IV. OVAL DISTORTIONS AND WARPS

In a substantial number of spiral galaxies the velocity field deviates from axial symmetry in a systematic bisymmetric pattern. Two kinds of patterns are seen, and in both cases the kinematical major axis (line of extreme radial velocities) changes its position angle as function of radius. If this change is in the inner parts usually there is misalignment with the major axis of some of the structures seen on optical photographs, the HI distribution in the outer parts is confined to the optically visible arm or ring structures and the kinematical major axis is not perpendicular to the kinematical minor axis. If this is the case we suspect an oval distortion to be the principal cause of the bisymmetric deviation from axial symmetry. If the change in the position angle of the kinematical major axis is in the outer parts the major axis of the inner regions is usually well aligned, the HI continues smoothly outwards beyond the optically visible material on sky limited plates and the kinematical minor axis is perpendicular to the kinematical major axis. If this is the case we suspect a warp in the outer disk, and since it is inferred from the kinematics we speak about a kinematical warp. Obviously the distinction is not watertight since both phenomena can occur in the same galaxy, and in a couple of cases this actually happens.

There is now more data around than at the time the above distinction was formulated. It appears necessary to consider various

subdivisions in both oval distortions and warps, basically to isolate properly the astrophysical problems on which the observations seem to have a bearing.

Oval distortions can be distinguished as follows:

- True bars like NGC 5383, NGC 3359 and the large southern ones. In these cases the HI data clearly lack angular resolution compared to the optical observations. The theoretically expected signature of the bar distortion in the velocity field is much more pronounced than the observed one. A promising way to get around this is to use surface photometry and optical spectroscopy to obtain parameters like bar strength etc., and to use the HI data to get a good estimate of the axisymmetric mass distribution in the outer parts. This approach has been tried for the best studied barred spiral, NGC 5383, by Duval and Athanassoula (1982), and can now also be done for the other barred spirals which have been observed in the HI with moderate angular resolution, such as NGC 3359 (Gottesman, 1982), NGC 3992 and NGC 4731 (Gottesman and Hunter, this volume), NGC 1097 and NGC 1365 (Van der Hulst et al, this volume) and NGC 1398 (Bosma, in preparation).
- Ovals (i.e. no classical bar visible in a blue photograph but a fat bar (oval) instead). Some of the kinematical properties of these galaxies are reminiscent of those of barred spirals. Clear examples are NGC 4151 (Bosma et al., 1977a), NGC 4258 (Van Albada, 1980) and NGC 4736 (Bosma et al., 1977b). Yet no bar but a strong oval can be seen in blue photographs. However, it may well be that in the red or near infrared one can detect such a bar. From plates of M83 taken by Ken Freeman one can easily see a steady progression in the dominance of the bar when one goes from the ultra-violet via blue and visual to the near infrared. Some of the pictures published by Elmegreen (1981) also show this.
- Suspected bar/oval systems. In these cases the velocity field has only a weak signature of an oval distortion i.e. small residual velocities when one subtracts the axisymmetric field based on the rotation curve from the observed field. The characteristic pattern for a bar distortion can still be noticed, as for example in NGC 3198 (Bosma, 1981a), but the bar is not very impressive and one has a hard time to convince skeptics about its existence. Often I suspect that galaxies where the axial ratio changes as function of radius, e.g. NGC 300 (De Vaucouleurs and Page, 1962) or IC 342 (Ables, 1971) have a weak oval in the central parts, but again the evidence in velocity data is not clearcut. Nevertheless these galaxies have been classified as SAB or SB galaxies by De Vaucouleurs (1963).

Warps can either be seen directly in some edge-on galaxies or argued on the basis of the kinematics. Kinematical warps are usually described in terms of tilted ring models, which were first introduced by Rogstad et al. (1974) for the galaxy M 83. Nowadays there are many more examples of warped HI disks being reported (cf. Bosma, 1981b), but it comes always as a bit of a surprise when one finds the next

one, like e.g. NGC 628 (Briggs, 1982). Several forms can now be distinguished:

- the simple integral sign form. Here the tilted ring models show a monotonic change in the position angle and inclination of the rings as function of radius. Good examples are M 83 (Rogstad et al., 1974), M 33 (Rogstad et al., 1976), NGC 300 (Rogstad et al., 1979) and NGC 2841 (Bosma, 1981a).
- a more complex shape with the plane crossed twice. The type example is the optical warp in NGC 4762 (cf. Sandage, 1961). Other examples argued on the basis of the kinematics are NGC 5055 and NGC 7331 (Bosma, 1981a).
- somewhere in between are the cases where the warp turns back a bit but does not cross the plane twice. New data by Sancisi (1982) show this to be the case in the direct warps of NGC 5907 and NGC 4565, although the effect is predominantly seen at one side.

It should be noted that although the direct warps of NGC 5907 and NGC 4565 do start approximately at the cutoff radius of the stellar disk this is not a universal phenomenon. Certainly in all the cases with complex shapes the warp starts well within the Holmberg radius. Also in the case of IC 342 (Newton 1980 b, c) the spiral structure extends into the warped region.

An interesting case of a galaxy with oval distortion and a warp has now been found by Wevers (1982) in his study of NGC 2903. There most of the HI strongly coincides with the outer arms, leaving gaps between these arms and the main optical disk quite similar to an oval galaxy like NGC 4151. But outside the strong outer arms there is faint HI emission with velocities clearly indicating the pattern of a kinematical warp. There is structure in this emission in the sense that one of the tilted annuli is rather pronounced in HI, and it will be interesting to find out whether this has something to do with the 1:1 resonance as e.g. discussed by Binney (1981).

V. ROTATION CURVES.

A compilation of HI rotation curves has been given in Bosma (1978, 1981 b). These curves go usually much farther out than curves determined from optical spectroscopy. However the sample of galaxies with good HI curves is much more heterogeneous than the samples discussed by Rubin and her collaborators. The curves are usually flat, also in the outer parts beyond the optical image, but effects of oval distortions, warping and asymmetries have to be taken into account. In the absence of successful dynamical models one has to be cautious in interpreting the results from e.g. tilted ring models. Moreover, in the central region of galaxies beamsmearing effects are important and therefore additional optical spectroscopy is necessary to obtain the correct rotation curve. For early type disk galaxies, like Sa's, no HI is detected in the inner parts, and sometimes there are no HII regions either, hence determination of the circular

velocity there might be very difficult. Absorption line data measure the mean velocity of the stars, and a full theoretical treatment involving also the velocity dispersion and the volume density of matter is necessary to obtain the circular speed. Thus a systematic study of HI rotation curves and the relationship with morphological types is rather difficult.

Comparison of HI and H α rotation curves is very useful since there is now much more overlap than 10 years ago. A technical problem is presented by galaxies having inclinations around 65°–80°. These are probably too inclined in order to use an intensity weighted mean HI velocity, but not inclined enough to justify use of the terminal velocity as is done for edge-on galaxies (cf. Sancisi and Allen, 1979). Resolution effects in the HI data play certainly a big role here. For UGC 2885 the HI data by Roelfsema and Allen (1983) do agree with the optical data by Rubin et al. (1980) if one ignores the inner parts and takes the HI peak velocity. For NGC 6503 Shostak et al. (1979) took the terminal velocity and obtained higher rotational values than those found later by De Vaucouleurs and Caulet (1982), although here the overlap in radius range is not that large. Certainly care has to be taken here, and it is desirable to construct geometrical models taking beamsmeearing into account, which then should be compared with the observations. The necessity for correcting the rotation curve becomes then obvious, as was the case for NGC 2841 and NGC 7331 (cf. Bosma, 1981 a).

There is some evidence for falling rotation curves in the far outer parts of some galaxies, although careful consideration indicates that this evidence is not as solid as one would wish. Already the data on NGC 891 presented by Sancisi and Allen (1979) indicated that the rotation curve in the outer parts beyond the optical image might drop. However this occurs only in the southern tail, which has no counter part at the other side. Similar asymmetries occur also in NGC 5907 and NGC 4565, though there the HI does extend beyond the optical image at both sides of the galaxy. Considerations about fitting a tilted ring model to these warped edge-on galaxies suggest that their warp is quite complicated and that if a drop is observed in the rotational velocity it is probably real. Another case where a drop-off has been found is in the galaxy NGC 5908 (Van Moorsel, 1982); here the drop is symmetric and might well be real. Since all these galaxies are seen edge-on, however, a couple of objections remain: 1) it is not clear whether the gas we see is actually on the line of nodes and 2) it is not clear whether the gas is in circular orbits. Therefore one has yet to be cautious in treating these observations as evidence for falling rotation curves.

Finally, a brief comment on the determination of the mass distribution from a rotation curve. There is much room for ambiguity here. Even if one takes e.g. a constant M/L for the disk, one still has the freedom to choose specific disk and halo models which all fit the handful of independent data points well. As an example for NGC

2841 one can calculate a halo+disk model in which $M_{\text{halo}}/M_{\text{disk}} \sim 2.8$ with a $(M/L)_{\text{disk}}$ of 5.8 which fits the observed rotation curve reasonably well. So if one wants to have $M_{\text{halo}}/M_{\text{disk}} = 10$ one has to go out to ~ 150 kpc or to reduce $(M/L)_{\text{disk}}$. Clearly we need other ways to determine the properties of the massive halo, if it exists, than rotation curves alone.

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DISCUSSION:

LINDBLAD: Would Dr. Sandage like to comment on the spiral rectification problem in M33?

SANDAGE : Humphries and I were impressed by the change in position angle of the ten optical arms as one goes outward. Your HI kinematic position angles seem to agree with this optical change if you add the far outer HI positional data of the Cambridge deep map (Newton et. al.) which continues the change of position angle beyond the outer optical arms. These, together with the double peaked HI profiles in the outer HI disk still suggest to us that a severe warp exists in the plane of the arm system as well as the HI disk. But the position angle of the old disk remains the one found by de Vaucouleurs, also according to the new work of the Lyon group.

BOSMA: I do not agree that the HI kinematical major axis follows the warp proposed on the basis of the rectification of the arms. There is a difference of at least 20° in position angle between the major axis

you propose and the one found in the Cambridge and Owens Valley 21-cm velocity fields in the inner parts of the optical disk. Such a situation seems to me irreconcilable, and therefore I'm inclined to abandon the underlying assumption you make i.e. that all the spiral arms in M33 are logarithmic. Of course I'm well aware of the warp in the HI layer farther out in M33 - beyond the optical image mainly - but the issue here is whether there is a severe warp in the inner 2 kpc where the restoring forces of the disk are quite strong.

BINNEY: Is it not true that in the standard Rogstad et al. ring models of kinematic warps, each ring rotates in its own plane? In reality the rings will wobble or precess and this contributes substantially to a kinematic warp. Thus we probably should not take particular ring models very seriously until they include more dynamics.

BOSMA: Yes, in principle you are correct. In practice the tilted ring models serve as a convenient geometrical description of the observations. Sometimes rotation curves based on tilted ring models are used e.g. to construct mass models, but one always has to be aware of the fact that non-circular motions are present in a warped disk.

TOHLIN: Would you comment on what fraction of HI disks show strong $m=1$ asymmetries, that is, how many disks show substantially more HI gas on one side of the galaxy's center than on the other?

BOSMA: There are not too many galaxies with strong $m=1$ asymmetries in the HI distribution. The paper of Baldwin et al. (see ref. in text) mentions 4 cases. There are several more with minor $m=1$ asymmetries, but I think the total fraction of strong asymmetries does not exceed 10-20% in the case of big spirals.

FEITZINGER: A displacement is often observed in late type galaxies between bar center and rotation center or between optical center and bar center (Feitzinger 1980, Space Science Rev. 27, 35). This may be also a reason for distortions. Do you have some detailed information on this type of distortions in your galaxy sample?

BOSMA: No, not much has been done on these, although there is some unpublished Westerbork work. The good examples are, as always, in the south (NGC 1313, NGC 4027, Magellanic Clouds).

RUBIN: A few years ago, I noticed that all galaxies with dynamical warps, those in your thesis and those published elsewhere were warped in the sense that with increasing radius the inclination became more edge-on. Does this curious circumstance still hold? Is it an observational artifact?

BOSMA: Yes, most of them become indeed more edge-on, but Van der Kruit tells me that NGC 1058 (pure face-on) is warped and there may now be more cases yet to be published. A given ring with a certain

column density in the main plane is more easily detected when it's more edge-on but I think we'll sooner or later find the ones where the outer rings become less inclined. If the edge-on's follow the tilted ring model they become more face-on at increasing radius.

KENNICUTT: Do you ever find galaxies that do not possess warps or distortions in HI?

BOSMA: There are still some regular galaxies. Roelfsema and Allen (in prep.) mapped the large Sc UGC 2885 and find it very regular. Also NGC 3198 (Bosma 1981a) is regular, with deviations from axial symmetry at the 5-10% level.

BAJAJA: The results of high resolution HI observation of M31 clearly show the presence of warps in this galaxy in the form of morphological distortions and overlapping of features along the line of sight. The consequence of these projection effects is the presence of more than one velocity component in almost every point of the galaxy. One has to be careful then in deriving the rotation curves and the velocity field from the mean velocities in the cases of galaxies with high inclinations and probable warping. In the particular case of M31 we noticed (Bajaja and Shane, *Astron. Astrophys. Suppl.* 49, 745) that there is large difference between the published rotation curves as derived from optical and from radio observations, the latter being much flatter than the optical. I would like to ask V. Rubin whether this situation has been modified specially in view of the results for Sb galaxies mentioned in her talk this morning?

RUBIN: There are several points to note. In the case of M31, our optical observations are of HII regions very near the major axis, with a very large range of nuclear distances. Thus the outer parts of the optical rotation curve come from HII regions well beyond those observed at 21-cm by you and Shane. For your 21-cm rotation curve, velocities for regions well off the major axis, closer to the nucleus on the plane of the sky, are deprojected to give the rotational velocities for large R. This deprojection can be treacherous, if non-circular velocities, warps, or other complex phenomenon are operating. The most meaningful comparison of optical and 21-cm observations will come when velocities can be compared region by region in the observed domain rather than in the projected domain.

For galaxies farther away, and hence of smaller angular size than M31, a similar problem can arise if the galaxy is viewed at relatively high inclination. If the angular size of the galaxy is on the order of 10 times the size of the 21-cm beam, then observations along the major axis may not suffer too severely from the effects of beam smearing. But for regions well off the major axis, beam smearing becomes a problem, for the velocity field is changing rapidly within a single beam. Hence if velocities from these fields are included in the derivation of the rotation curve, I would expect significant differences from those observed optically along the major axis of the galaxy.