"The best of all people have shown us innumerable bends in galaxies. I'm not saying how that is done; all I do is bend the galaxy."

M.S. Roberts in Discussion III.4

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THE THREE-DIMENSIONAL DISTRIBUTION OF NEUTRAL HYDROGEN IN M31

Robert N. Whitehurst,* Morton S. Roberts, and Thomas R. Cram
National Radio Astronomy Observatory†
Green Bank, West Virginia

Given the wealth of data, the rotation curve, and the necessity for out-of-plane hydrogen demonstrated in the preceding paper, it seems desirable to attempt to establish a systematic procedure for determining the three-dimensional distribution of hydrogen. Under the assumption of cylindrical rotation this is, in principle, possible for most of the galaxy.

The standard equation for the radial velocity of a point in cylindrical rotation may be inverted to yield

$$(V_{rot} \sin i)/R = (V_R - V_S)/x,$$

where the x axis is chosen to coincide with the major axis of the projected ellipse and x is constant for a line of sight. With a known rotation curve, $(V_{rot} \sin i)/R$ as a function of R and its inverse $R((V_{rot} \sin i)/R)$, single valued over most of its range, can be determined. Thus, from the measured quantities V_R, V_S, and x we determine R. From R and x we find y, with an ambiguity in sign. From y and the sky coordinates (λ, β) of the line of sight it is easy to calculate z, the distance from the nominal plane of the galaxy. Thus a radial velocity observed in a line of sight at position on the sky (λ, β) can be associated with a point (actually one of two points) in the rotating system.

Figure 1(a) shows a series of profiles taken on M31 at constant λ or x, here 10 kpc from the minor axis toward the southwest. Note that there are at least three prominent velocity features and that some profiles are complex, indicating that the line of sight is intercepting more than one concentration. The velocities expected for an in-plane material are indicated by tick marks on the profiles. Figure 1(b) is

* On leave from the Department of Physics and Astronomy, the University of Alabama.
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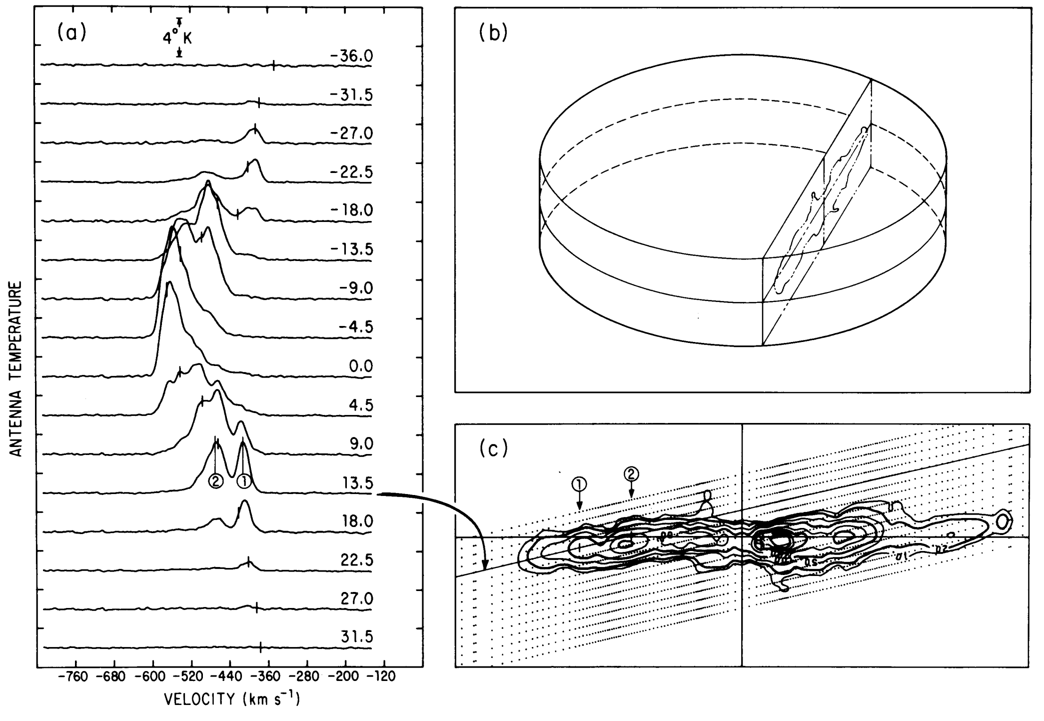

Figure 1(a). Profiles taken at λ = -49ʹ.5. Tick marks on profiles indicate velocities expected of in-plane material.

(b). Schematic representation of the plane sampled by the observations of (a).

(c). Contour map of volume density of neutral hydrogen in the plane indicated in (b) from modeling the profiles of (a). See text for meaning of symbols.

a schematic representation of the geometry. The series of observations defines a plane perpendicular to the major axis. Each line of sight may intercept hydrogen at any point along its path through the galaxy, and each point will have its own radial velocity.

The antenna temperature of a given velocity channel is proportional to the beam-averaged surface density of hydrogen atoms having velocities within that channel and thus, neglecting dispersion, within a fixed line-of-sight range. The surface density may, therefore, be converted to a volume density. Figure 1(c) is a contour map of the volume density in the plane indicated in (b) determined by a channel-by-channel modeling of the set of profiles of (a). The horizontal, or y, axis lies in the nominal plane of the galaxy parallel to the minor axis. The vertical, or z, axis is parallel to the axis of rotation. The negative (south preceding) major axis points through the origin out of the paper. The

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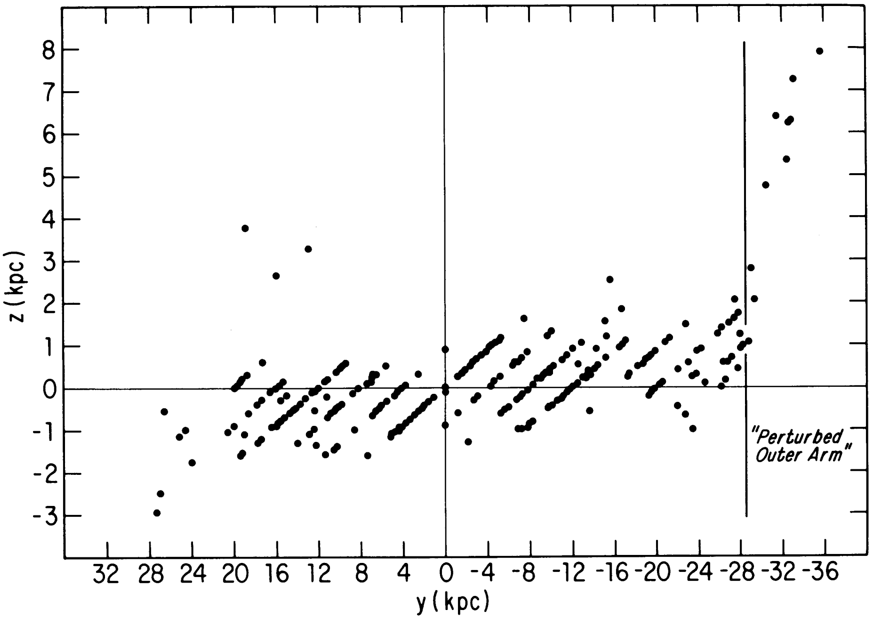

Figure 2. Points in galaxy associated with peaks in velocity profiles as viewed from direction of negative major axis.

dotted lines represent lines of sight, each dot at the point associated with a particular velocity channel.

Consider the line of sight at β = 13°.5 and the resulting profile. The association between hydrogen concentrations and peaks in the profiles is clear. Two such associations are identified by the circled numbers. The most obvious characteristic of this cross section is its thickness, here approximately doubled by the finite beam. Measurements made through hydrogen concentrations give a typical z extent to half density, corrected for beam size, of about $\pm$ .7 kpc. To a density of about one atom per liter, a typical z extent is about $\pm$ 2 kpc, and measurable hydrogen is sometimes found more than 5 kpc from the conventional plane.

We have applied the same techniques to the determination of points in the galaxy corresponding to peaks in the velocity profiles. Although density information is lost, these points should indicate locations of significant hydrogen densities. Figure 2 is a view of this array of points from the direction of the negative major axis. Again, the horizontal axis lies in the conventional plane. Several characteristics stand out. Again, hydrogen is found at considerable distance from the conventional plane. The "edge" is typically a kiloparsec from the plane. Secondly, the hydrogen appears to be inclined slightly to the conventional plane. It appears that an inclination of 79° is a better fit to the hydrogen distribution over much of the galaxy than is the 77° assumed here. Finally, there are a number of points which depart

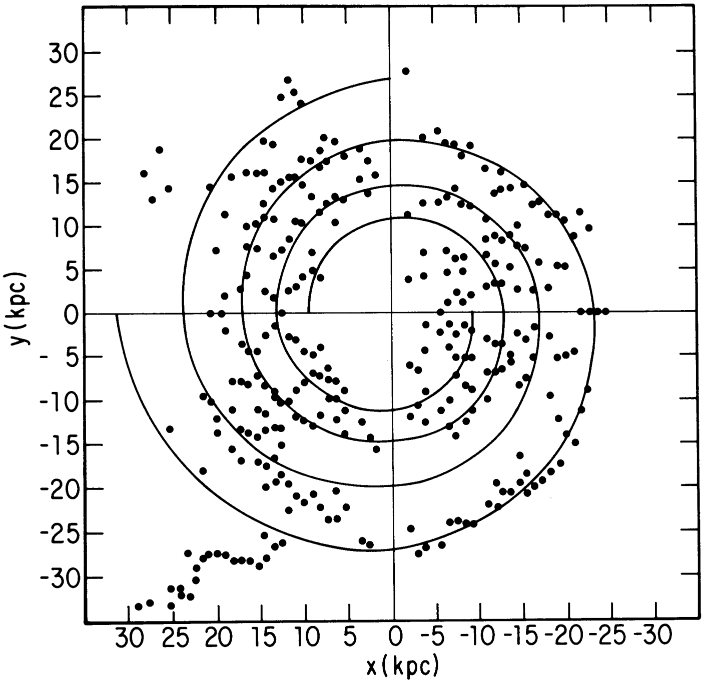

Figure 3. Face-on view of same array of points as in Figure 2. Spiral is R = 85 exp(0.0962θ).

rather violently from the plane. The three isolated points in the upper left are identified with isolated features on profiles and probably do not belong to Andromeda. At a velocity of about 115 km s^{-1} they may represent a high-velocity cloud. The series of points running up and to the right, dubbed the "perturbed outer arm", represents a feature which appears in each form of data representation as a smooth extension of normal features. For this reason, we feel that it probably is connected with M31 but probably does not follow the general rotation field.

Figure 3 presents a face-on view of the array of points. Some structure appears, particularly a feature which appears to be Baade's S7 arm and which may be traced here beyond the minor axis. The series of points which diverges from this is the "perturbed outer arm" group. We have attempted to fit a spiral to these points. The fit is at best only fair, with apparent bridges between arms. The spiral, strictly empirical, is somewhat tighter than that fitted by Arp to the HII regions, but his spiral is a poorer fit to our data.

DISCUSSION FOLLOWING PAPER III.5 GIVEN BY R.N. WHITEHURST

GIOVANELLI: You mentioned that the "outer perturbed arm" could be anywhere along the line of sight; therefore it could be either foreground gas escaping from Andromeda or behind the disk and falling into it. Is that correct?

WHITEHURST: Yes, that is correct.

GIOVANELLI: In addition, would that change the location that you proposed for it in the (x,y) plane?

WHITEHURST: Yes, because there is an ambiguity in the sign of y.

VISSER: You said that the full thickness of the arm at half-intensity is approximately 1.4 kpc. Does the velocity dispersion of the gas support this?

WHITEHURST: I did not estimate the velocity dispersion from the observations. This model is a purely kinematic representation; it gives velocity dispersions of up to 10 km/s. A dynamicist might tell if this supports the number for the arm thickness.

TOOMRE: As Visser implied, surely it takes a vertical r.m.s. speed of 30 or 50 km/s (or its pressure equivalent) to thicken your inner gas layer to the 1.4 kpc that you estimate. And yet horizontally you seem to imply or assume a dispersion only of the order of 10 km/s. How do you reconcile those numbers?

M.S. ROBERTS: Clearly, there are two problems: how do you get the gas up there, and how do you keep it.

WHITEHURST: I think all we maintain is: it is there!

KERR: The thickness of 1400 pc is worrisome. The treatment is based on an assumption of cylindrical rotation. Have you considered how things would change if this assumption is relaxed?

M.S. ROBERTS: A lower velocity (as for the globular cluster system in our own Galaxy) will reduce the z-extent.

WESTERHOUT: With an "effective" beamwidth of 2 kpc, it seems rather impossible to be able to distinguish between a 1.4 kpc halfwidth of the layer and a much thinner layer with 1 - 2 kpc outriggers in the z-direction (like our own Galaxy). Any thin layer will simply be smoothed in with the wider distribution, and therefore any value of scale height derived from this work should be taken with a massive grain of salt.

M.S. ROBERTS: In this sort of modeling we have both radial velocity information as well as extensive positional information. Values of the z-extent have been corrected for a finite beam. The resultant value which is about half the beam size should be little effected by the finite beam size.

EMERSON: With reference to your deduced thickness (in the z-direction) of the HI distribution, the high resolution Cambridge observations imply an HI thickness increasing more or less linearly with radius, being $\sim$ 500 pc at R = 12 kpc and 2 or 3 kpc at R $\simeq$ 25 kpc.

SANCISI: The question of the scale height of the gas in normal disk galaxies has already come up several times in discussions during this symposium. The best observational conditions for determining the z-structure are, of course, offered by a galaxy which is seen almost completely edge-on. This is the case of NGC 891, where the HI disk in the inner part is essentially unresolved by the 26" (= 1.7 kpc) Westerbork beam. The full width at half-intensity of the neutral hydrogen layer must therefore be less than 1 kpc; a thickness of 250 pc, as found in our galaxy, would be consistent with the present observations. A similar thickness is also found for the narrow component of the radio continuum disk in NGC 891 at 6 cm by Allen et al. (A.A., in press). In the outer parts of the system the HI layer seems to become thicker: the full width may go up to about 2 or 3 kpc.

SHANE: ANOMALOUS MOTIONS OF SPIRAL ARMS IN M31

The central region of M31 has been observed in the 21-cm line using the Westerbork Synthesis Radio Telescope. The observations were made by Dr. E. Bajaja and a preliminary report has been published by Shane (1975, La Dynamique des Galaxies Spirales, ed. L. Weliachew, p. 257). There are 15 maps at velocities between -600 and -40 km/s at intervals of 40 km/s. The present results were derived from maps convolved to a 54" (FWHP) circular beam, on which the noise level was about 0.4 K.

The double-peaked profiles discovered by Bajaja (see Shane 1975) can be seen on these maps to arise from two HI components, easily distinguishable over most of the north-preceding side of the galaxy. One is concentrated to the spiral arms and shows rotational properties in rough agreement with published rotation curves (e.g. Emerson 1976, M.N.R.A.S. 176, 321). It shows deviations, however, in the sense that the prominent dust arm at 5 kpc from the center is moving inward with a velocity of 30 km/s whereas the bright arm at 9 kpc is moving outward at 20 km/s. These motions are seen unambiguously on the minor axis and are confirmed elsewhere. The simplest explanation invokes an explosion in the nucleus about 3×10^7 years ago, giving both arms an outward impulse. The outer arm would still be moving outward whereas the inner arm would have passed its apocenter.

The second component shows no correlation with optical features, virtually no velocity gradient perpendicular to the line of nodes, and a velocity gradient parallel to the line of nodes indicative of a distance of about 25 kpc from the center. This suggests that we are seeing a warped or thickened outer ring projected upon the central part of the disk. Analysis of single-dish measurements (M.S. Roberts, this symposium) leads to similar conclusions. Within the limited range of the WSRT survey no analogous feature is found on the south-following side of M31.

VAN DER LAAN: Have you or anyone else any suggestions as to how an explosion or anything else could transfer momentum of such large coherent magnitudes? What are the linear scales in the plane of the galaxy?

SHANE: The dark arm is about 5 kpc and the main arm 9 kpc from the nucleus. I agree that momentum transport over this distance is a problem, and this is one reason that I don't take the model seriously. I mentioned it only because it provides a simple and possibly suggestive means of representing the observations. Several more plausible (but unfortunately much more elaborate) models have been suggested.

WRIGHT: Have you seen anything which could be interpreted as high velocity clouds in M31?

SHANE: No, our sensitivity is not sufficient to really hope for that.

EMERSON: Cambridge observations do show some high velocity clouds.

WRIGHT: How much mass is involved?

EMERSON: Very little.

DAVIES: The high velocity cloud I found near M31 had dimensions of $\sim 0\overset{\circ}{.}5$, a systemic velocity of -450 km/s and a central column density of a few times 10^{19} cm^{-2}.

GIOVANELLI: How far are the high velocity clouds in M31 from the disk?

EMERSON: That is a model-dependent number, so I can't say.

GIOVANELLI: Are they related to the "outer perturbed arm" mentioned by Dr. Whitehurst?

EMERSON: No, there are two isolated blobs in the extreme NE without any relation to other arms.