# 8. DENSITY DISTRIBUTION AND THE RADIAL VELOCITY FIELD IN THE SPIRAL ARMS OF M 31

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**Abstract.** The density distribution and the radial velocity field in the Andromeda galaxy, M 31, have been studied on the basis of the 21-cm radio-line data from Jodrell Bank and Green Bank. The true density has been obtained from the observed one by solving a two-dimensional integral equation. As the resolving power of the radio telescopes is too low to locate all spiral arms separately, optical data on the distribution of ionized hydrogen clouds have been also used. The mean radial velocities have been derived by solving a two-dimensional non-linear integral equation with the help of hydrogen densities, and a model radial velocity field.

The inner concentrations of hydrogen form two patchy ringlike structures with mean radii 30′ and 50′, the outer concentrations can be represented as fragments of two *leading* spiral arms.

The rotational velocity, derived from the radial velocity field, in the central region differs considerably from the velocity curves obtained by earlier authors. The difference can be explained by the fact that in this region the correction for the antenna beam width is much greater than adopted by previous investigators.

## 1. Introduction

In the present paper the density distribution and the radial velocity field of neutral hydrogen in the Andromeda galaxy, M 31, have been studied. The investigation is based on the 21-cm radio-line data from Jodrell Bank and Green Bank Observatories, kindly sent to us by Dr. R. D. Davies and Dr. M. S. Roberts. Optical data on the distribution and motion of ionized hydrogen are also used.

When studying the distribution and motion of hydrogen in external galaxies it is necessary to take into consideration the angular resolving power of radio telescopes. Gottesman *et al.*, (1966) found that the correction for the beam width of the 250-feet Jodrell Bank telescope both in the density and the velocity does not exceed 10%. Our calculations, however, have shown that in some cases the correction needed is much greater. This indicates that the Jodrell Bank investigators have used too simplified reduction method. The Green Bank data have been reduced neglecting the antenna smearing effect (Roberts, 1966). For that reason the available radio data are to be reduced once again. At present the program is not finished. In this paper the preliminary results are reported.

## 2. The Integral Equations for the Density and the Mean Radial Velocity

Let $X$, $Y$ be the rectangular galactocentric coordinates in minutes of arc, the $Y$-axis being directed to the NE side of the major axis of the galaxy; $V$ the true radial velocity; $D(X, Y)$ the true projected density of neutral hydrogen; $E(V-\bar{V})$ the distribution function of residual radial velocities in the direction $X$, $Y$; $\bar{V}=\bar{V}(X, Y)$ is the mean radial velocity in this direction.

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The radio telescope, directed to the point $X_p$, $Y_p$ and disposed to the frequence, corresponding to the radial velocity $V_k$, will record the flux

$$T(X_p, Y_p, V_k) = \iiint_{-\infty}^{+\infty} D(X, Y)\, F(X - X_p, Y - Y_p) \times E[V - \bar{V}(X, Y)]\, G(V - V_k)\, \mathrm{d}X\, \mathrm{d}Y\, \mathrm{d}V\,, \tag{1}$$

where $F(X-X_p,\ Y-Y_p)$ is the angular sensitivity function of the telescope and $G(V-V_k)$ is the corresponding frequency sensitivity function.

Integrating (1) over all observed velocities $V_k$ we obtain the observed projected density of hydrogen $\bar{D}(X_p, Y_p)$, which is connected with the true density $D(X, Y)$ by means of the equation

$$\bar{D}(X_p, Y_p) = \iint_{-\infty}^{+\infty} D(X, Y)\, F(X - X_p, Y - Y_p)\, \mathrm{d}X\, \mathrm{d}Y\,. \tag{2}$$

This is a two-dimensional homogeneous Fredholm integral equation of the first kind for the determination of the true density $D(X, Y)$. If the density is known the Equation (1) can be considered as a non-linear integral equation for the determination of the mean radial velocity $\bar{V}(X, Y)$.

The observations of point radio sources indicate that the function $F$ can be fairly well approximated by a two-dimensional Gaussian with half-intensity diameters 15′ and 10′ in the case of the Jodrell Bank and Green Bank telescopes respectively (Davies, 1969; Roberts, 1969). The function $G$ has in the case of the Jodrell Bank telescope also a Gaussian shape with half-intensity width 200 kHz, which correspond to a velocity dispersion of 17 km $\mathrm{s}^{-1}$. The Green Bank telescope has a rectangular shaped function $G$ of 95 kHz = 20 km $\mathrm{s}^{-1}$ wide.

## 3. The Density Distribution

From the analogy with our Galaxy we may expect that the neutral hydrogen in M 31 is concentrated in the spiral arms. The optical observations of ionized hydrogen (Baade, 1963; Arp, 1964) indicate that the Andromeda galaxy has 4 or 5 spiral arms in both sides of the galaxy. The mean distance between every two arms is 20′ = 4 kpc, in projection only 4′–8′, except the region around the major axis. The ionized hydrogen arms coincide with the neutral hydrogen arms within the actual distance of 5′; the neutral hydrogen arms are situated closer to the centre of the galaxy (Roberts, 1967).

The resolving power of the radio telescopes used is not sufficient to separate all spiral arms in the Andromeda galaxy; only the most dense arms N 4, S 4, and S 5 (designated after Baade, 1963) can be 'seen' individually (Roberts, 1967). To locate the other neutral hydrogen arms the optical data on the distribution of the ionized hydrogen clouds (Baade and Arp, 1964) can be used.

The true density distribution has been determined from the integral Equation (2) by two methods. Near the minor axis the equidensity lines are almost parallel to the major axis, and the two-dimensional equation can be reduced to the one-dimensional one. Representing the observed density distribution by a sum of Gaussian functions we get the solution of the equation also in the form of a sum of Gaussian functions.

For points far off from the minor axis the solution of the Equation (2) has been found by successive approximations. The arms have been located by combining optical and radio data, the corrected densities have been derived from the observed radio densities by a trial-and-error procedure. The densities have been found for a network of points, placed in $X$ and $Y$ at intervals 2′ and 10′ respectively.

The observed (Green Bank) and corrected density profiles (first approximation) along the major and minor axes of the Andromeda galaxy are shown in Figures 1 and 2 respectively. The picture is quite similar to the neutral hydrogen density profiles found for our Galaxy; an example of them, drawn on the basis of the Dutch survey (Westerhout, 1957; Schmidt, 1957), is given in Figure 3.

The $X$, $Y$-distribution of ionized hydrogen clouds (Baade and Arp, 1964) is given in Figure 4. The map of equidensity contours of neutral hydrogen is presented in Figure 5. The $R$-distribution (integrated over all position angles $\theta$) of the neutral and ionized hydrogen, as well as of the stellar associations (Van den Bergh, 1964) is plotted in Figure 6. The original distributions are reduced to an equal total number of objects, $N = 1000$.

The inspection of the data obtained leads us to the following conclusions:

(a) the spatial distribution of neutral hydrogen is similar to the distribution of

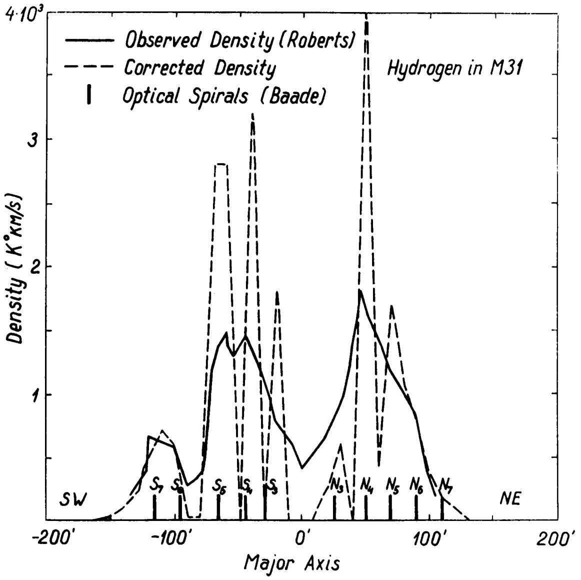

Fig. 1. The observed (Roberts, 1967) and corrected surface densities of neutral hydrogen along the major axis of M 31. The location of optical arms according to Baade (1963) is also indicated.

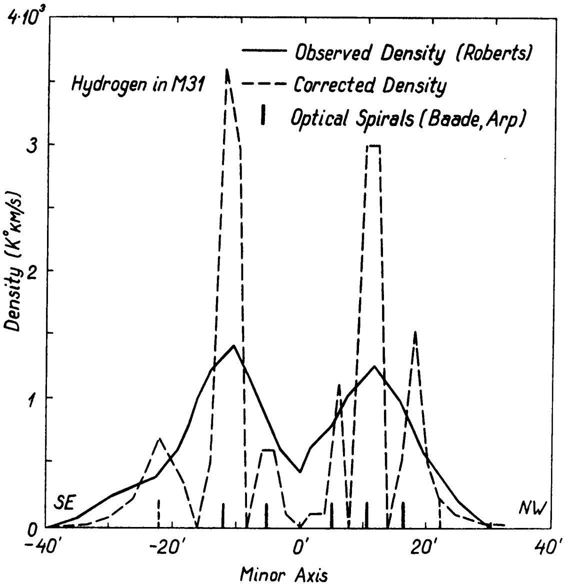

Fig. 2. The observed and corrected surface densities of neutral hydrogen along the minor axis of M 31.

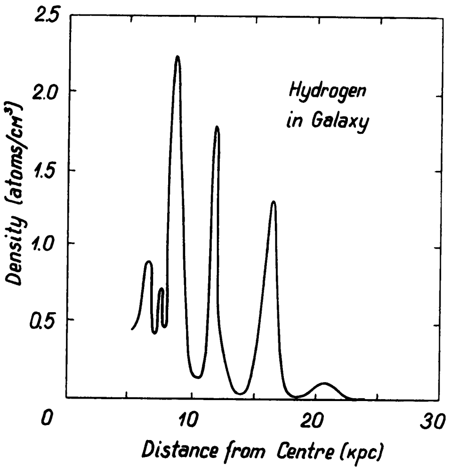

Fig. 3. The space density of neutral hydrogen in the plane of our Galaxy.

ionized hydrogen and stellar associations; at great distances from the centre the relative density of neutral hydrogen is higher than that of the ionized hydrogen;

(b) the inner concentrations of hydrogen form two patchy ring-like structures with the mean radii 30′ (the arms N 3, S 3 after Baade) and 50′ (the arms N 4, S 4);

(c) the outer hydrogen concentrations can be fairly well represented as fragments of two *leading* spiral arms S 5–N 6, N 5–S 6.

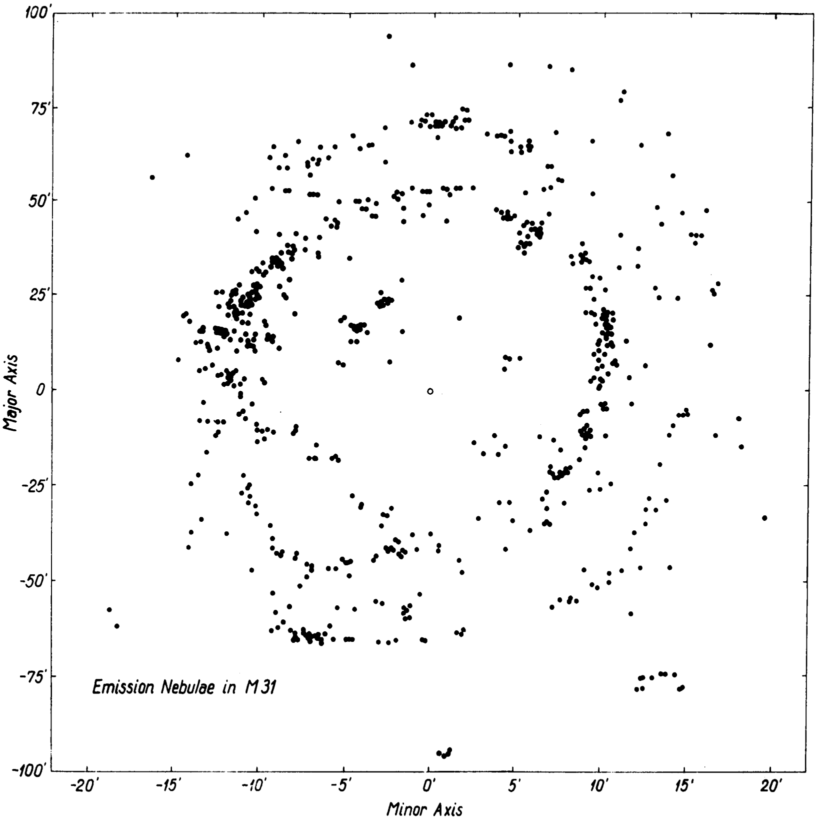

Fig. 4. The distribution of ionized hydrogen clouds in M 31 according to Baade and Arp (1964) data. The scale in $X$ (minor axis) is enlarged 4.5 times, corresponding to a tilt angle 12°.8 of M 31.

## 4. The Radial Velocity Field

The density distribution function $D$, and the angular sensitivity function $F$ are independent of the velocity $V$, and in Equation (1) we can integrate first over the velocity

$$T(X_p, Y_p, V_k) = \int\int_{-\infty}^{+\infty} D(X, Y)\, F(X - X_p, Y - Y_p) \times H[V_k - \bar{V}(X, Y)]\, \mathrm{d}X\, \mathrm{d}Y, \tag{3}$$

where

$$H[V_k - \bar{V}(X, Y)] = \int_{-\infty}^{+\infty} G(V - V_k)\, E[V - \bar{V}(X, Y)]\, \mathrm{d}V. \tag{4}$$

If the velocity dispersion is independent of the position $X$, $Y$, the Formula (3) can be made more suitable for numerical computations. Let us use instead of $X$, $Y$ the

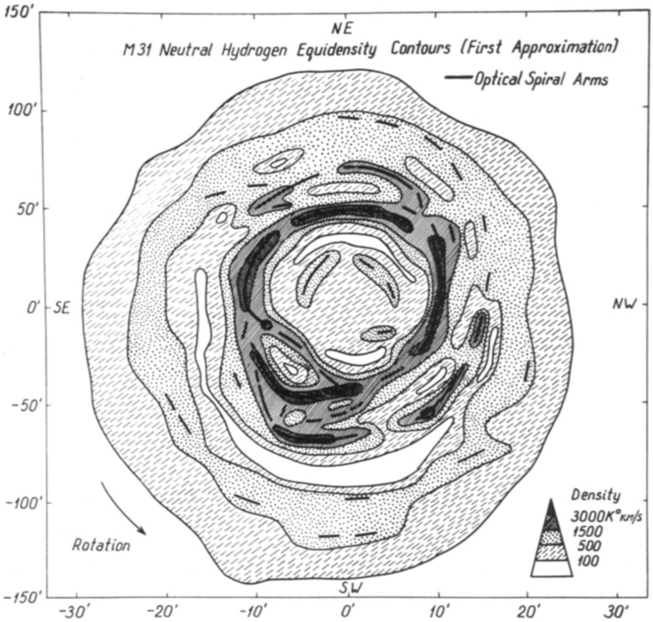

Fig. 5. The preliminary equidensity contours of neutral hydrogen in M 31. Main spiral optical arms are indicated by dark lines.

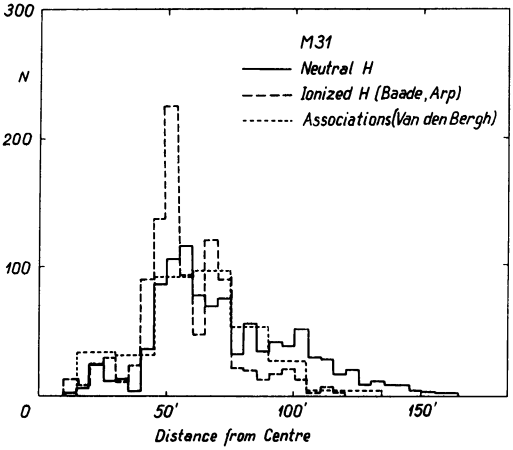

Fig. 6. The distribution of neutral hydrogen, ionized hydrogen clouds (according to Baade and Arp, 1964), and of stellar associations (Van den Bergh, 1964) in M 31.

variables $S$, $\bar{V}$, where $S$ is the length along the line $\bar{V}(X, Y) = \text{const}$. We have

$$T(X_p, Y_p, V_k) = \int_{-\infty}^{+\infty} H(V_k - \bar{V}) \times \left[ \int_S D(X, Y)\, F(X - X_p, Y - Y_p)\, J\left(\frac{X, Y}{S, \bar{V}}\right) \mathrm{d}S \right] \mathrm{d}\bar{V} . \tag{5}$$

Assuming the Gaussian form both for the functions $G$ and $E$ with the dispersions $\sigma_G$, $\sigma_E$, respectively, then the function $H$ has also the Gaussian form with the dispersion

$$\sigma_H^2 = \sigma_G^2 + \sigma_E^2 . \tag{6}$$

Interferometric observations show (Deharveng and Pellet, 1969) that the radial velocity dispersion has practically a constant value $\sigma_E = 17$ km s$^{-1}$ (due to the projection effect the dispersion $\sigma_E$ is greater than the true radial velocity dispersion in a small volume element of the galaxy).

Formula (5) has been used to calculate the theoretical 21-cm line profiles. An effective radial velocity dispersion $\sigma_H = 24$ km s$^{-1}$, the corrected hydrogen density field, and a model radial velocity field have been used. The radial velocity field has been calculated from a plane disc pure rotation model, using the obvious formula

$$\bar{V}(X, Y) = V_0 + V(R)\frac{Y}{R}\cos i , \tag{7}$$

where $V(R)$ is the circular velocity at the distance $R$ from the centre of the galaxy, $V_0$ – the mean radial velocity of the galaxy, and $i$ – the tilt angle of the plane of symmetry of the galaxy to the line of sight. The velocity $V(R)$ was taken from our four-component model of the Andromeda galaxy (Einasto and Rümmel, 1969), the constants are chosen as follows: $i = 12\overset{\circ}{.}8$, $V_0 = -300$ km s$^{-1}$.

Gottesman *et al.*, (1966) have derived for 231 points $X_p$, $Y_p$ the line profiles (spectra) $T(V_k \mid X_p, Y_p)$. For all these points the theoretical profiles have been calculated. These are quite similar to the observed profiles, but, in general, shifted in the velocity. The comparison of the profiles enables us to correct the model radial velocity field.

In this way we have found a solution to the integral Equation (1). From the corrected radial velocities near the major axis points a new improved rotation velocity curve has been derived.

The results are presented graphically. In Figure 7 the 21-cm line profiles for a major axis point are given. The theoretical profiles are calculated by using both the corrected and the uncorrected (observed) hydrogen densities, the model velocity field being identical. Mean radial velocities and the point velocity $V_p$ (the model radial velocity at the point $X_p$, $Y_p$) are also indicated. In Figure 8 the rotation curves are presented, and in Figure 9 the model and observed radial velocity field.

The analysis of the results can be summarized as follows:

(a) the change of the density causes both vertical and horizontal shifts in the line profiles, therefore an unbiased radial velocity field can be derived only by using carefully corrected densities;

(b) when the radio telescope is directed to a point of low hydrogen density or large density gradient, the mean radial velocity of the profile does not coincide with the point velocity; in extreme cases near the major axis the difference exceeds 100 km s$^{-1}$. This effect has caused large systematic errors in the previous reductions of radio-data (Argyle, 1965; Gottesman *et al.*, 1966; Roberts, 1966);

(c) the corrected radial velocity field has great irregularities in respect of the model field.

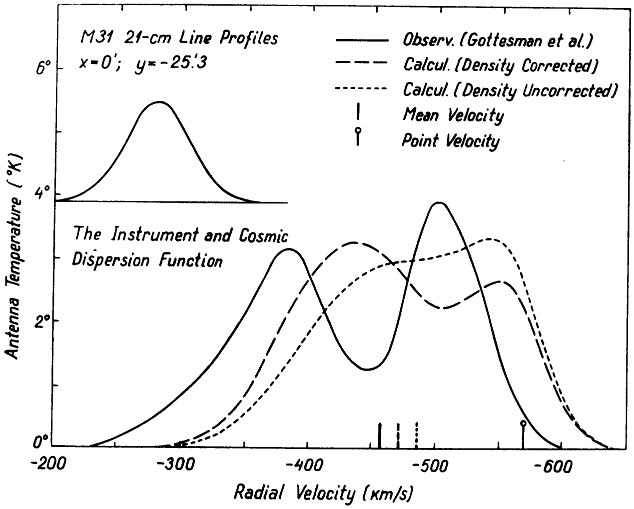

Fig. 7. The 21-cm radio line profiles for a major axis point of M 31. The instrumental and cosmic dispersion function is indicated.

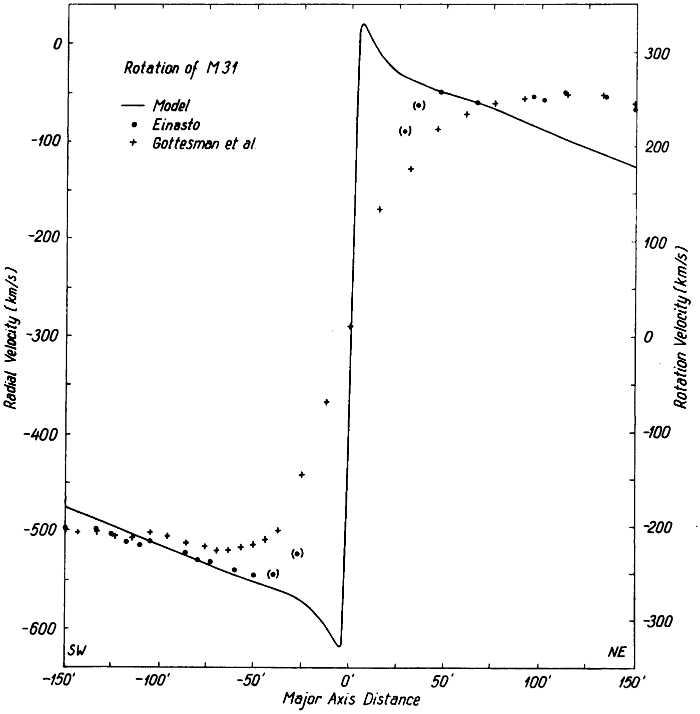

Fig. 8. The model circular velocity and rotational velocities according to Gottesman *et al.*, (1966) and our present data.

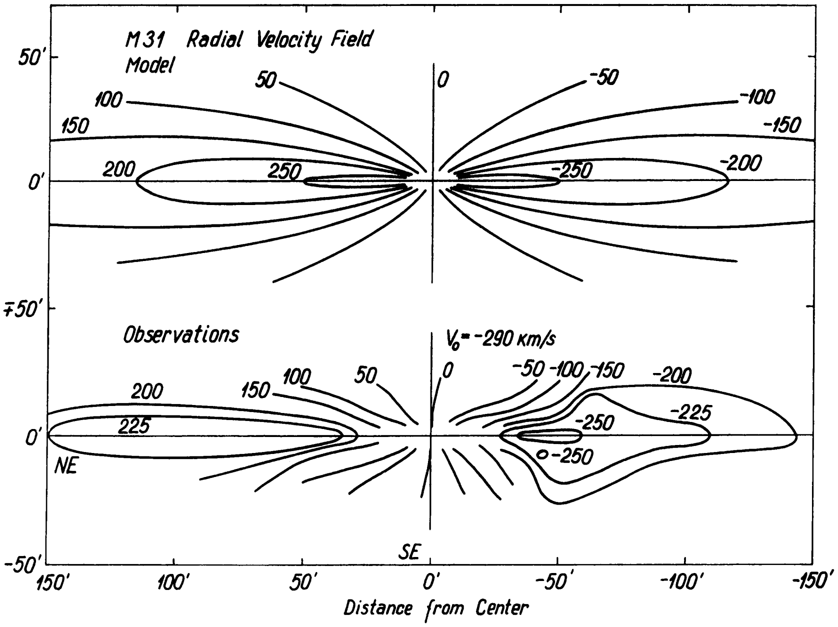

Fig. 9. The observed and model radial velocity fields in M 31.

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