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NEUTRAL HYDROGEN IN M 51

BY J. HEIDMANN[1])

21-cm line observations of Messier 51 made with the Dwingeloo telescope are reported. The recession velocity is 485 km/sec; assuming the distance to be $4c$ Mpc where c is an unknown correction factor, the total hydrogen mass is found to be $8.4 \times 10^8 c^2 M_\odot$. A comparison between the M_H/L values for various extragalactic systems is made in section 5.

1. *Introduction*

Earlier measurements at Dwingeloo for extragalactic 21-cm line radiation have been described by van de Hulst, Raimond and van Woerden (1957, referred to as paper I), Volders (1959), Wentzel and van Woerden (1959), Muller (1959) and Volders and Högbom (1961). Here we discuss measurements on M 51 (NGC 5194-95) performed in May 1959 by the author and in February 1960 by Dr J. A. Högbom. Because of the considerable redshift of M 51 it was necessary to change the first local oscillator frequencies in the receiver. They were set by Prof. C. A. Muller so that the receiver sweeps the frequency band from ($f_0 - 1.54$) to ($f_0 - 7.10$) Mc/s, where f_0 is the line rest frequency. However, on the low-velocity side a few measurements could be made with the normal set-up. Technical information is given in Table 1.

Table 1

period	May 1959	February 1960
number of one-hour measurements with 1 comparison channel	0	38
with 2 comparison channels	124	67
bandwidth (kc/s)	150	140
distance between measuring channel and comparison channel (kc/s)	1080	1440

Each day sensitivity tests were conducted on Cassiopeia A with the broad-band continuum receiver. The tests were performed and reduced by Mr Hin; they show that the sensitivity did not change by more than 5%, mainly through temperature variations. This variation is negligible compared to the large errors arising from other sources, as will be shown below.

The variation of sensitivity as a function of frequency was also measured by Mr Hin, using the continuum part of the receiver (150 kc/s bandwidth) with Cas A as a reference. With the shifted frequencies the intensity scale cannot be linked directly to the usual Dwingeloo reference, which is the main top of the profile at $l^1 = 50°$, $b^1 = 0°$, because this maximum is outside the frequency range.

The link was made by comparing the intensity of Cas A at a certain position in the shifted frequency band with that in the normal band, using the receiver noise temperature as a standard. The assumption is made that the intensity of Cas A and the receiver noise temperature do not change over the range of frequencies used.

By this process Mr Hin obtained curves giving the sensitivity as a function of the second local oscillator frequency. For the 1959 measurements they range from about 24 to 31 units (see preceding paper; 1 unit ≈ 1° K in T_b) per full scale of the pen recorder for oscillator frequencies between 23 and 29 Mc/s. There are four such curves for one comparison channel either at 1080 or 1440 kc/s above or below the measuring channel. They differ from one another only by a shift in the oscillator frequency. For two comparison channels the sensitivity is $\sqrt{2}$ times the

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average of that with one channel. For the 1960 measurements, the dependence on frequency is practically negligible.

2. *Errors*

The determination of μ (the mean error of the intensity for a 12-minute measurement with two comparison channels arising from the receiver noise, paper I) is very important, because the measured intensities are so small here that knowledge of the errors is fundamental. We made a specially thorough analysis of our 1959 data, which also included 85 hours of recording on M 77 and M 104. From the observed μ-values we have to subtract quadratically the reading errors arising from the averaging by eye estimate of the 12-minute recordings. When using two comparison channels, this reading error is of the order of 0.03 units; when using one comparison channel it is somewhat larger. On the μ-values which we shall get, this gives a correction of the order of 0.5×10^{-2} units, a very small correction indeed. In Table 2 the μ-values obtained from a statistical treatment of the measurements (cf. paper I) are given. The first line shows the results obtained for measurements with two comparison channels. The μ-distribution is somewhat more pointed than a gaussian distribution; therefore, on the second line, we give another gaussian determination of μ, such that 68 % of the measurements have an error smaller than μ. On the third line the value of μ, obtained from our 57 measurements with one comparison channel, is given. In the last column the standard deviation on μ, defined by $\Delta\mu = \mu / \sqrt{2N}$ where N is the number of measurements, is tabulated.

TABLE 2

Errors (expressed in 10^{-2} units)

	μ	N	$\Delta\mu$
2 channels, gauss	13	150	0.8
2 channels, 68%	12	150	0.7
1 channel, gauss	16	57	1.4
M 104	13	57	1.2
M 51, general	16	19	2.5
M 51, detailed	14	117	0.9
theoretical value	13-14		

Other determinations of μ can be obtained from the r.m.s. dispersion of the intensity measurements, especially where the intensity T is expected to be independent of the frequency. This is the case for M 104: here one should have a very wide and flat line profile (see Appendix). As the intensities are small compared to the errors, they can be assumed to be constant; their r.m.s. dispersion gives the values indicated on line four of Table 2. The statistical analysis of the M 51 data, which is made below, yields the 5th and 6th lines of Table 2. All these experimental values of μ are coherent and agree well with the theoretical value (MULLER 1956). For the receiver used here, MULLER gives a noise factor $N = 2.3$; allowing for 20 to 30% spillover (VOLDERS 1959, MULLER 1959) this gives $\mu = 0.13$ to 0.14 units.

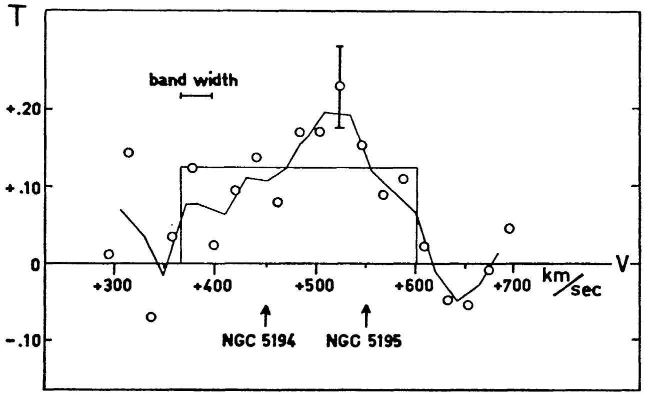
In the following we shall adopt $\mu = 0.14$ units, including reading errors.

3. *Results on velocities*

In 1959, a point $\frac{1}{4}$° North of the centre of M 51 (NGC 5194) was observed for 27 hours, because we were interested in the faint extensions which show towards the North of NGC 5195, but no conclusive result was obtained.

Of the 97 (1959) and 105 (1960) measurements on M 51, averages within 100 kc/s bands are shown in Figure 1 as "apparent brightness temperatures", assuming 1 unit = 1° K in T_b, according to the preceding paper. Equal weight is here given to the two series. Apparent brightness temperature is defined as the weighted average of the true brightness temperature of the object over the main beam of the antenna. The main beam is defined as the part of the antenna pattern $f(\vartheta, \varphi)$ within which $f(\vartheta, \varphi)$ is everywhere $\geq 0.01 \, f(0,0)$. The abscissae are velocities with respect to the local standard of rest (MACRAE and WESTERHOUT 1956). We have plotted the curve joining the averages of successive pairs of points, in order to provide some smoothing. The arrows mark the optical velocities (HUMASON, MAYALL and SANDAGE 1956).

FIGURE 1



We indicated also the r.m.s. error and the bandwidth. The 1959 values, which were obtained with the comparison channels at a distance of 1080 kc/s from the measuring channel, have been corrected when there was hydrogen line-radiation in a comparison channel. With reference to the discussion given in the Appendix, we may approximate the

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measured profile by a rectangle. Considering the errors there is no point in trying a more complicated shape. The sum of the squares of the deviations of the intensities I from the rectangle is

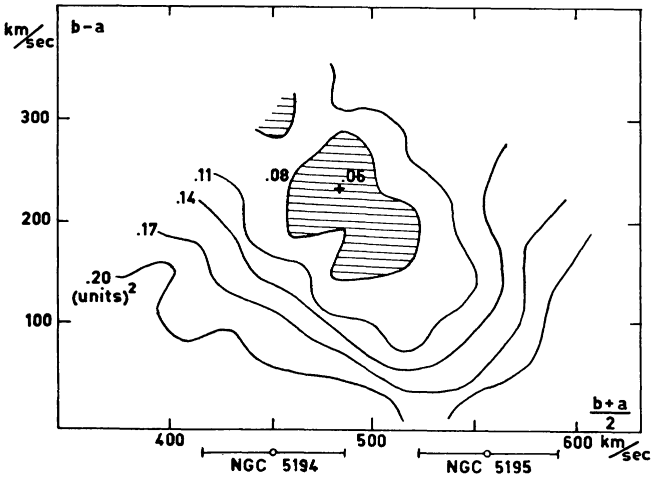
$$U = \sum_{\text{out}} I^2 + \sum_{\text{in}} (I - m)^2,$$

where m is the height of the rectangle, $\sum_{\text{out}}$ and $\sum_{\text{in}}$ are the summations outside and inside the velocity range covered by the rectangle. When the measurements are uniformly distributed in velocity, U can be written:

$$U = \sum_{\text{total}} I^2 - \frac{\left(\sum_{\text{in}} I\right)^2}{n},$$

where n is the number of measurements inside the rectangle. From the data, U can be calculated as a function of the velocity limits a and b of the rectangle. The most probable rectangle will be the one corresponding to a minimum of U. This was done for the 19 points of Figure 1, excluding the last one to the right because of its low weight. In Figure 2 we give a contour map of U as a function of the centre position $(a+b)/2$ and the width $(b-a)$ of the rectangle.

FIGURE 2



The minimum of U is: $U_{min} = 0.06$ (units)^2; theoretically it is equal to $N\left(\sqrt{\frac{5}{4\nu}}\,\mu\right)^2$ (paper I) where $N = 19$ is the number of points and $\nu = 9.5$ is the mean number of one-hour measurements with two channels per point. This gives $\mu = 0.16$ units (Table 2, line 5). The variance of U_{min} is $U_{min} \cdot \sqrt{2/N} = 0.02$ (units)^2; this is indicated by the hatched region in Figure 2. Unfortunately this region extends to the upper left, which prevents the errors to be small; more measurements would be needed on the low-velocity side. However, the plot shows that the most probable value for the radial velocity of M 51 is $+485$ km/sec, with respect to the local standard of rest.

The most probable value for the width of the rectangle is 230 km/sec; as the inclination of the nebula on the plane of the sky can be as small as 30°, it is compatible with usual rotational velocities.

The rectangle corresponding to the minimum of U (Figure 2) has been drawn in Figure 1.

The determination of μ which we just obtained has a very large uncertainty because each of the 19 points was already the mean of many measurements. To obtain a more precise value for μ we can study the distribution of all two-channel measurements inside the most probable rectangle. The mean square deviation of these 117 recordings from their average gives $\mu = 0.14$ units (Table 2, line 6).

4. *Results on hydrogen content*

The total line intensity is given by the integral $\int I dV$ of the observed profile. This integral is given by the general weighted mean of the measured intensities multiplied by the width of the velocity range investigated: $\int I dV = 34$ units. km/sec. The relative error is $\sqrt{\frac{5}{4n}} \cdot \frac{\mu}{I} = 15\%$, where n is the number of one-hour measurements with two comparison channels plus half the number with one channel. If the source is quite small compared to the beam, the total amount of hydrogen is given by (WENTZEL and VAN WOERDEN 1959):

$$M_{\text{H}} = 1.53\, s^2 \int T dV \quad \text{solar masses},$$

where s is the distance of the galaxy in kpc. Assuming $s = 4000\, c$ (SÉRSIC 1960), where c is an unknown correction factor to the distance, and 1 unit in I = 1 °K in T, we obtain:

$$M_{\text{H}} = (8.4 \pm 1.3) \times 10^8 c^2 M_{\odot}.$$

If the nebula is not a point source but, for instance, a uniform disk of diameter 12′, M_{H} should be increased by 10%. This correction will be omitted here since we do not know the brightness distribution across the source. No correction for self-absorption is attempted.

The measurements are not in agreement with those made by HEESCHEN (1957), who finds a twenty times higher intensity. It appears probable that his result is spurious.

5. *Comparison between extragalactic nebulae*

In Table 3 some data concerning the extragalactic systems observed at Dwingeloo are represented together with data on the Magellanic Clouds and two globular clusters. The photographic magnitudes m^*_{pg} have been corrected for interstellar absorption,

TABLE 3

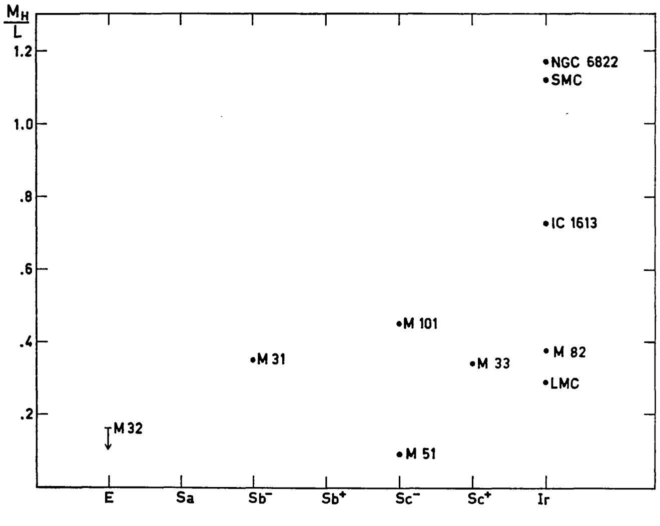
Comparison of extragalactic systems and two globular clusters

object	type	m^*_{pg}	gal. lat. b	Δm	m_{pg}	dist. (kpc)	L (solar units)	M_H (solar units)	M_H/L
M 31	Sb^-_a	4.33_a	-21	0.2_f	4.1	$630\ c_j$	$1.3 \times 10^{10} c^2$	$4.5 \times 10^9 c^2_j$ 3)	0.35
M 32	E_a	9.06_a	-22	0.2	8.9	$630\ c_k$	$1.6 \times 10^8 c^2$	$< 2.5 \times 10^7 c^2_k$	< 0.16
M 33	Sc^+_a	6.19_a	-31	0.5	5.7	$630\ c_l$	$2.9 \times 10^9 c^2$	$1.0 \times 10^9 c^2_l$	0.34
M 51	Sc^-_a $IrII_a$	8.66_a	-68	0.3_h	8.4	$4000\ c_m$	$9.8 \times 10^9 c^2$	$8.4 \times 10^8 c^2_p$	0.09
M 82	$IrII_a$	9.20_a	$+41$	0.4_h	8.8	$2600\ c_n$	$2.9 \times 10^9 c^2$	$1.1 \times 10^9 c^2_n$	0.38
M 101	Sc^-_a	8.20_a	$+59$	0.3_h	7.9	$2600\ c_l$	$6.6 \times 10^9 c^2$	$3.0 \times 10^9 c^2_l$	0.45
NGC 6822	IrI_a	9.21_a	-20	0.6_h	8.6	$500\ c_n$	$1.3 \times 10^8 c^2$	$1.5 \times 10^8 c^2_n$	1.15
IC 1613	IrI_a	10.00_a	-60	0.2_h	9.8	$630\ c_n$	$6.7 \times 10^7 c^2$	$4.9 \times 10^7 c^2_n$	0.73
LMC	Ir	0.74 1)	-33	0.4	0.4	$46\ c_o$	$2.1 \times 10^9 c^2$	$6 \times 10^8 c^2_o$	0.29
SMC	Ir	2.72 2)	-45	0.4_i	2.3	$46\ c_o$	$3.6 \times 10^8 c^2$	$4 \times 10^8 c^2_o$	1.12
Coma cluster in beam	—	9.8_q	$+87$	0.2	9.6	$89000\ c_r$	$1.6 \times 10^{12} c^2$	$< 3 \times 10^{12} c^2_r$	< 1.8
M 3	gl. cl.	7.21_s	$+77$	0.0_t	7.2	$14\ c_t$	$3.6 \times 10^5 c^2$	$< 7 \times 10^2 c^2_g$	$< 2 \times 10^{-3}$
M 13	gl. cl.	6.78_s	$+40$	0.6_t	6.2	$7\ c_t$	$2.3 \times 10^5 c^2$	$< 2 \times 10^2 c^2_g$	$< 1 \times 10^{-3}$

References to Table 3: a. HOLMBERG 1958; b. EGGEN and DE VAUCOULEURS 1956; c. DE VAUCOULEURS 1957; d. ELSÄSSER 1959; e. ELSÄSSER 1958; f. BAADE, private to OORT; g. ROBERTS 1959; h. HOLMBERG 1950; i. DE VAUCOULEURS 1955; j. SCHMIDT 1957; k. WENTZEL and VAN WOERDEN 1959; l. VOLDERS 1959; m. SÉRSIC 1960; n. VOLDERS and HÖGBOM 1961; o. KERR *et al.* 1954; p. this paper; q. HEIDMANN, unpublished; r. MULLER 1959; s. CHRISTIE 1940; t. ARP 1955; u. VAN DE HULST *et al.* 1957.

either by the cosecant law or by other estimates (Δm in Table 3), to yield the photographic magnitude m_{pg} in column 6. The magnitude of the Coma cluster of galaxies results from weighting the light-distribution by the Dwingeloo beam. Taking the absolute photographic magnitude of the Sun to be 5.37 (STEBBINS and KRON 1957), we obtain the absolute luminosities L expressed in solar units. With the aid of the values for M_H we find in the literature, we can calculate the hydrogen mass–luminosity ratio M_H/L for the various systems. The quantity M_H/L is independent of the correction factor c and affords a fair comparison between the objects. In Figure 3 the ratios M_H/L are shown as a function of nebular type. The values indicate a rather small dispersion for quite different types of galaxies.

FIGURE 3



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APPENDIX

Shape of the line profile of a galaxy

We assume:

a) the galaxy has an axis of rotational symmetry;

b) the hydrogen density projected on a plane perpendicular to the axis equals $n(r)$ cm^{-2} for $r \leq R$ and is zero for $r > R$, where r is the distance to the axis;

c) there is no expansion; the rotational velocity is $\Theta\ (r)$.

The effect of the inclination i of the axis of the galaxy on the line of sight is simply to multiply the abscissae in the line profile by sin i; let us therefore suppose that the galaxy is seen edge-on.

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1) This is an average of the following three determinations: 0.72_b, 0.64_c and 0.86_d.

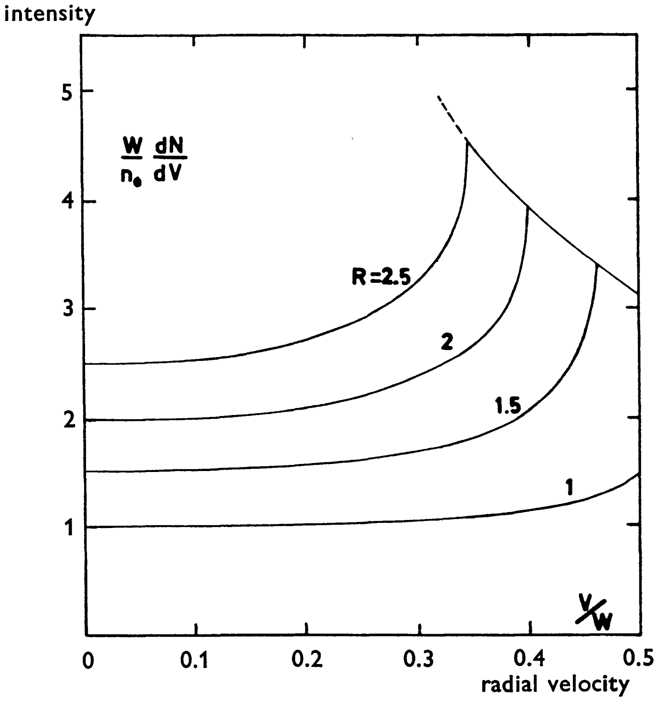
2) This is an average of 2.59_c and 2.86_e.

3) This value is obtained from 2.5×10^9_u by correcting for changed distance and intensity scales.

The radial velocity of a point at (r, φ), where φ is the position angle with respect to the Earth, is $V = \Theta(r) \sin \varphi$.

For usual shapes of the function $\Theta(r)$, the surface $V =$ constant cuts the plane $\varphi = \pi/2$ at two values r' and r'' of r.

FIGURE 4



The number of hydrogen atoms dN having their radial velocity in the range $(V, V + dV)$ is then given by:

$$\frac{dN}{dV} = 2 \int_{r'}^{\rho} \frac{n\, r\, dr}{\sqrt{\Theta^2 - V^2}},$$

where $\rho = R$ if $r' < R < r''$ and $\rho = r''$ if $r'' < R$. We have chosen $r' \leq r''$. The case $R < r'$ simply gives $dN/dV = 0$.

Simple functions, but sufficiently realistic for our purpose, are $\Theta = \frac{Wr}{r^2 + 1}$ and $n = \frac{n_0}{r^2 + 1}$; r is taken unity at the maximum of Θ.

We so obtain a $\sin^{-1}$ function and Figure 4 shows the numerical results for various values of R. To these line profiles should be added the bandwidth smoothing of the receiver.

Typical values are $W \approx 700$ km/sec and $R \approx 1.5$; the band-width is $\approx 0.04\, W$. We see that, taking into account the large errors of the measured values, the line profile may be considered as a flat rectangle.

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