1959BAN....14..339M

BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS

1959 DECEMBER 14 VOLUME XIV NUMBER 493

COMMUNICATION FROM THE NETHERLANDS FOUNDATION FOR RADIO ASTRONOMY AND THE OBSERVATORY AT LEIDEN

21-CM OBSERVATIONS ON THE COMA CLUSTER

BY C. A. MULLER

Observations of the 21-cm hydrogen line from the Coma cluster of galaxies did not show any radiation. The accuracy of the measurements corresponds to a mean error in antenna temperature of 0.05 °K. From this result it is concluded that for a field of 0.25 square degrees at the centre of the cluster the ratio of neutral hydrogen mass to total mass is less than 0.03, if the radial-velocity dispersion of the hydrogen is 1000 km/sec.

Introduction

The present investigation of 21-cm hydrogen-line radiation from the Coma cluster of galaxies was instigated initially by the report of hydrogen-line radiation from this cluster by HEESCHEN (1956). It was thought desirable to have independent confirmation of the weak radiation found by HEESCHEN, and it was hoped that with our larger telescope some fine-structure in the intensity distribution over the cluster might be found.

A first attempt was made in August 1957, using the Dwingeloo 25-metre radiotelescope and our 21-cm receiver, modified for this purpose. The reported radiation of 2 °K should have been easily detectable, but no signal was found. Radar interference occurring on our image frequency limited our sensitivity to about 0.5 °K.

Further attempts were made in January and July 1958 with improved equipment. Again our observations were limited by radar interference. Observations were made on two frequencies which were free from interference, but no radiation was found with a mean error of 0.1 °K on these frequencies. From the higher accuracy obtained and the better method of observations it was concluded that the results obtained by HEESCHEN might have arisen from a spurious effect (MULLER 1959).

The measurements presented here were made in May 1959 with partly new equipment, which will be described in the next section. The measurements have been extended to a number of frequencies around 1388.9 Mc/s, the frequency corresponding to the optically determined radial velocity of 6657 km/sec (HUMASON, MAYALL and SANDAGE 1956).

It was also hoped that we would be able to set a still lower limit to the hydrogen radiation from the cluster, but due to unexpected zero-level drifts during the measurements the same or slightly larger mean errors for the individual points were obtained. Again no radiation from the cluster could be detected.

Receiver

The receiver used for these measurements was a single-conversion super-heterodyne receiver based on the same switching principle as our receivers for galactic and extra-galactic observations (MULLER and WESTERHOUT 1957).

The main difference is the use of tunable oscillators in the local oscillator of the receiver in stead of the normal crystal-controlled fixed oscillators. The electronic switch and the frequency-multiplier chain were those of our normal receiver; these parts had already been designed to be tunable between 1330-1430 Mc/s. Tuning of the local oscillator to any frequency in this range was possible within a few minutes. No swept-frequency operation of the receiver was provided, since it was found from our extra-galactic work (VAN DE HULST, RAIMOND and VAN WOERDEN 1957), that fixed-frequency observations were to be preferred.

In contrast to the normal procedure the local oscillator was operated on the high-frequency side of the signal to eliminate radar interference coming in on our low-frequency image, which had troubled us during previous measurements. Except for one day no clear interference was detected, though some weak interference seems to have occurred during a few nights.

Behind the normal wide-band 30 Mc/s intermediate-frequency amplifier two narrow-band i.f. amplifiers centred on 29.4 and 33.0 Mc/s were used. The pass band of both amplifiers was determined by three flat-coupled double-tuned circuits, to obtain a fairly square pass band with good suppression of interference on neighbouring frequencies. The overall bandwidth was 0.6 Mc/s.

These i.f. amplifiers were followed by the normal arrangement of 400 c/s amplifier, low-pass filter, d.c. amplifier and recorder.

In general a time constant of one minute was used during the observations.

A new front end, mounted in a small light-weight box behind the feed antenna, was used, consisting of a coaxial 21-cm isolator (17 db reverse loss, 1.3 db forward loss), a broad-band coaxial crystal mount and a four-stage wide-band 30 Mc/s amplifier with cascode input. The design was the same as used in our normal receiver except for the use of an isolator in the antenna line.

The use of an isolator was based on the following arguments:

When no signal is received, the recorder in general still shows a deflection which is a function of frequency. This deflection with respect to the present d.c. level will be called the zero level. This zero level is due to the general effect that the high-frequency load admittance across the mixer crystal is a function of frequency and is thus not the same on the two frequencies between which the receiver is continually switching.

If the mixer is adjusted for minimum noise figure this admittance change when switching from one frequency to the other gives a change in input voltage on the grid of the cascode input tube and thus produces a spurious 400 c/s signal at the output of the i.f. amplifier. The load admittance consists of two components: the load admittance with the antenna pointed towards free space (not mounted in the focus) and a component due to the reaction of the parabolic reflector on the antenna admittance (SILVER 1949).

The change of the "free-space" load admittance may be minimized by proper broad-band matching between antenna and mixer mount, but the second effect cannot be compensated for. This gives a zero level which, if the i.f. frequency is fixed, varies sinusoidally with frequency with an amplitude depending on the frequency difference of the two local oscillator frequencies. For our 25-metre telescope, which has a focal length of 12 metres, the reflector introduces a reflection coefficient in the antenna line of $\Gamma = 0.01$; the phase changes 2π for a change in receiver tuning of 12 Mc/s. For a frequency difference of 6 Mc/s the change of the reflection coefficient is $\Delta\Gamma_s = 0.02$. The same effect occurs on the image frequency $\Delta\Gamma_i = 0.02$. The two effects have to be added vectorially. The zero-level amplitude may then be calculated from the formula

$$\Delta T_2 = 2\left|\overline{\Delta\Gamma}_s + \overline{\Delta\Gamma}_i\right| . \frac{T_{eff}}{L}, \qquad (1)$$

where L is the sum of high-frequency and conversion losses and T_{eff} is the effective receiver input temperature. The maximum value of the zero-level deflection expressed in degrees antenna temperature is about 25 °K, and thus is large compared to a signal of the order of 0.1 °K which we want to observe.

Effects of this order actually occurred in our first measurements, which were made with the normal broad-band front end, without an isolator.

Using an isolator with forward loss L_f and reverse loss L_r gives a reduction of the $\Delta\Gamma$'s in the load admittance of $\sqrt{L_r . L_f}$, corresponding to a factor of about 8 times for the isolator used, and gives an increase of T_{eff} to 1200 °K. ΔT_{max} becomes about 5 °K, a decrease in amplitude of about 5 times.

Since both T_{eff} and the mixer conversion loss are a function of temperature, this reduction of ΔT_2 would mean an increase in receiver stability in spite of the increase in noise temperature.

The expected reduction in amplitude of ΔT_2 due to the reflector reaction did occur and an amplitude reduction of about 5 times was found. The "free-space" zero-level deflection however showed unexpected drifts with ambient temperature, which are not yet completely explained, but seem at least partly due to the temperature dependence of the isolator. These drifts offset the expected gain in zero-level stability and no actual gain in stability was obtained. Except for some improvements in the broad-band matching of the high-frequency system, further improvement seems possible only by means of temperature stabilization in the receiver front end.

The front end was sufficiently wide-band to make no adjustments necessary when shifting from 1420 Mc/s to the Coma frequencies around 1390 Mc/s. Changing frequency thus meant only changing the local-oscillator frequencies.

The frequency calibration of the local-oscillator frequencies was done on the fourth harmonic of the frequencies of the tunable oscillators, using the calibration system normally used for the tunable second local oscillator of the galactic 21-cm receiver, as this fourth harmonic is within the tuning range of this local oscillator. The two frequencies were made equal to 10-kc/s standard-frequency-harmonics in the 26-Mc/s range. The two local-oscillator frequencies were thus known multiples of 0.540 Mc/s with an accuracy of about 5 kc/s.

The sensitivity of the receiver was measured using Cas A as a standard noise source and assuming equal sensitivity on signal and image frequencies.

It was found that without any retuning the sensitivity dropped only 10% when tuning from 1420 Mc/s to 1390 Mc/s.

The receiver noise was found to be equivalent to 1280 °K, with the assumption that the antenna temperature for Cas A is 300 °K. This value for Cas A is a preliminary value. It is 10% lower than would be expected from the flux of Cas A at 21 cm published by WESTERHOUT (1956), which, in view of new calibrations (MEZGER 1958) and other considerations, seems to be somewhat too high.

The theoretical r.m.s. noise amplitude on the record, using one i.f. channel is given by the formula (MULLER 1956)

$$\Delta T = \frac{\pi}{2} \cdot T_{eff} \cdot (\Delta\nu \, . \, \tau)^{-\frac{1}{2}} = 0.33\,^{\circ}\mathrm{K}, \qquad (2)$$

where $\Delta\nu$ is the i.f. bandwidth and τ is the time constant in seconds.

Observing procedure

The method of observation resembles closely the method used in all our extra-galactic work on 21 cm. During each measurement the two local-oscillator frequencies were kept constant by the observer within 5 kc/s, which meant occasional readjustment of the oscillator frequencies. The telescope was set 20 minutes on the centre of the Coma cluster ($\alpha = 194^{\circ}.63$, $\delta = 28^{\circ}.30$) and then for the same interval on one comparison field, then again on the cluster, then on the other comparison field and so on.

Two comparison fields were used alternately ($\alpha = 180^{\circ}.00$, $\delta = 28^{\circ}.30$ and $\alpha = 210^{\circ}.00$, $\delta = 28^{\circ}.30$). Each measurement on one frequency lasted between two and three hours.

The first measurements were made using a frequency difference between the local-oscillator frequencies about equal to the difference in centre frequencies of the two i.f. channels of 3.6 Mc/s (the actual difference of the local-oscillator frequencies used was 3.72 Mc/s), and the two-channel mode of operation was used (MULLER and WESTERHOUT 1957). In the later measurements a larger frequency difference of 5.40 Mc/s and only one i.f. channel (at 29.4 Mc/s) was used, since it was thought desirable to use a larger difference if possible. The value of 5.4 Mc/s was a convenient value since this difference corresponded to a difference of 0.100 Mc/s on the calibration frequency.

To obtain the best temperature stability and to eliminate any effects of interference due to solar radiation in switched far-side lobes, all observations were made during the night.

A complete table of all measurements is given below.

Reduction

If one observation consists of N intervals of 20 minutes

$$a - b - c - d - e - \ldots\ldots\ldots$$

and the intervals b, d, ... are measurements on the cluster, the observed signal with respect to the comparison fields is given by

$$\frac{1}{N-2}\left[b - \tfrac{1}{2}(a+c) - c + \tfrac{1}{2}(b+d) + \ldots\ldots\right] . \qquad (3)$$

This method allows for a uniform drift during the observation.

From each 20-minute interval the first 3 minutes were left out in the reduction to eliminate the exponential voltage change due to the time-constant filter. The remaining interval was divided into four equal parts, and the mean value over the interval was determined from these four readings. No difference between the two comparison fields was found, and all measurements were reduced as if only a single comparison field had been used in the observations. The resulting observed antenna-temperature differences between the centre of the cluster and the comparison fields are given in the table below.

To obtain an approximate mean error for the individual measurements we determined the mean error for each interval of 20 minutes from the differences between the values of each 4-minute interval and the mean over the whole interval.

This mean error, which we will call μ, is tabulated in the table below and may be directly compared with the theoretical value which may be derived from formula (2) by setting the time constant equal to half the observing time (VAN DE HULST, RAIMOND and VAN WOERDEN 1957). We then find for single-channel observations:

$$\mu_{theor.} = 0.10\,^{\circ}\mathrm{K}$$

and for double-channel observations

$$\mu_{theor.} = 0.07\,^{\circ}\mathrm{K}.$$

We see that for most observations μ is slightly larger than these theoretical values, indicating that instrumental effects like drifts influence the observations.

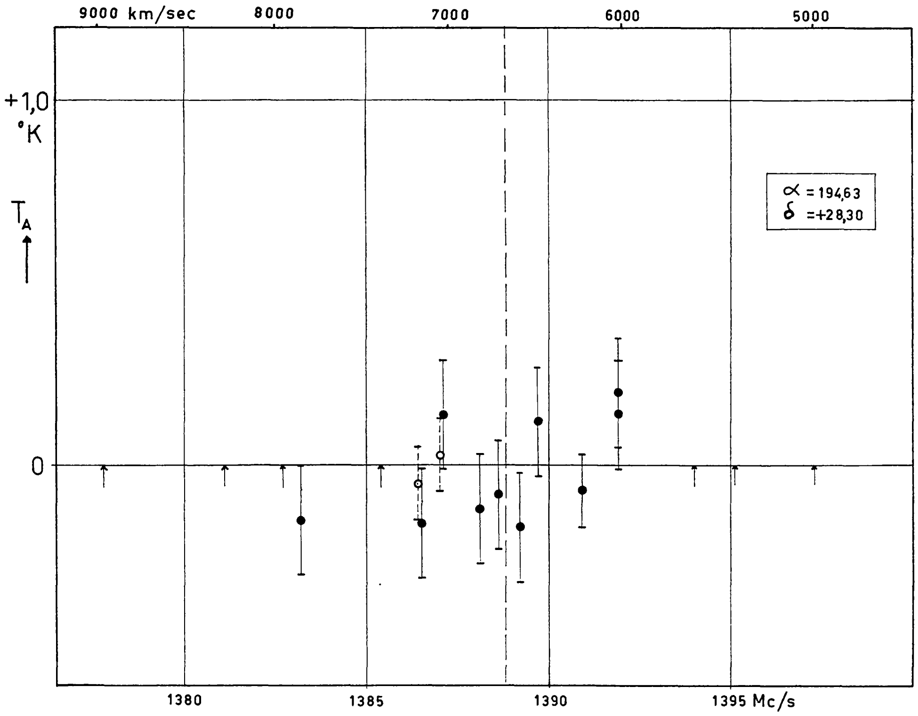
If we assume the noise on the record to be purely random, it is possible to derive from the mean error over one interval, μ, the mean error of each observation ΔT by means of the relation

$$\Delta T = \frac{\mu}{(N-2)}(4N-11)^{\frac{1}{2}} \quad N \geq 4 \qquad (4)$$

where N is the number of intervals. The mean error thus obtained is given in the table as the mean error ΔT.

Because the algebraic average of the observed differences ΔT_a is negligibly small, we can also use these values to compute a mean error for one observation. Since the calculated mean errors for the various observations do not differ very much, we may give all observations the same weight in this computation. We then find a mean error for each observation of 0.15 °K, which is indeed somewhat larger than the mean errors calculated from the values of μ. The cause of this larger error seems to be the occurrence of slow non-uniform drifts in several measurements, which influence the resulting antenna-temperature difference more strongly than the value of μ, which is deduced from intervals of only 16 minutes. This value of 0.15 °K for the mean error of each observation is used in the table for all measurements except the second one, which had a lower value for μ than all other observations and showed less drift; for this measurement we have assumed a mean error of 0.10 °K.

The observed antenna-temperature differences and their mean errors are also given in the figure. In this figure our previous results (MULLER 1959) have also been indicated by open circles and broken lines.



The observed antenna-temperature differences as a function of frequency. Estimated mean errors are indicated by vertical lines. The open circles and broken lines give the results of our earlier observations. The broken vertical line gives the frequency corresponding to the optical recession velocity. The arrows indicate the comparison frequencies of the single-channel observations.

Number	Signal frequency	Comparison frequency	V km/s	N	μ	ΔT	ΔT_a
7612	1387.11	1383.42 1390.80	7017	6	0.10	0.09	+ 0.14 ± 0.15 °K
7613	1390.89	1387.20 1394.58	6219	7	0.09	0.07	− 0.07 ± 0.10
7618	1389.18	1385.40	6580	7	0.14	0.12	− 0.17 ± 0.15
7619	1389.72	1395.12	6465	7	0.14	0.12	+ 0.12 ± 0.15
7623	1391.88	1397.28	6010	5	0.12	0.12	+ 0.14 ± 0.15
7624	1388.10	1382.70	6807	3 + 6	0.13	0.11	− 0.12 ± 0.15
7625	1391.88	1397.28	6009	7	0.13	0.11	+ 0.20 ± 0.15
7628	1386.48	1381.08	7149	7	0.11	0.09	− 0.16 ± 0.15
7629	1388.64	1394.04	6692	7	0.12	0.11	− 0.08 ± 0.15
7632	1383.24	1377.84	7832	7	0.11	0.09	− 0.15 ± 0.15

Interpretation of the results

The dispersion of the radial velocities of the galaxies in the central part of the cluster has been found to be about 1000 km/sec (SCHWARZSCHILD 1954; ZWICKY 1957). If we assume the velocity distribution of the neutral hydrogen to be gaussian with the same dispersion, the expected hydrogen line profile will have a width of about 10 Mc/sec. This means that all observations, except perhaps the last one, would be on the central part of the expected profile and we may use all these observations together to determine the mean antenna temperature for the central part of the expected profile. For all observations together we find

$$\Delta T_a = -0.02 \pm 0.05\,^\circ\mathrm{K}\ (\mathrm{m.e.}). \qquad (5)$$

We may conclude that our observations give an upper limit for the antenna temperature of 0.05 °K. To reduce this antenna temperature to the mean brightness temperature over the field of 0.25 square degrees covered by our antenna beam, which has a half-power width of $0^\circ.57$, we have to apply two corrections. To convert antenna temperatures into brightness temperatures the antenna temperature has to be multiplied by a factor of $(1 - \beta)^{-1}$, where β is the spill-over factor, which is estimated to be about 0.25 – 0.30. A second correction is necessary because the observed ΔT_a's are actually the differences between the antenna temperatures on two frequencies 5.4 Mc/sec apart (except for the first two observations where two comparison frequencies were used 3.6 Mc/sec above and below the signal frequency). Because of the large width of the profile the comparison frequencies will still lie in its wings. The observed T_a will therefore be smaller than the antenna temperature on the signal frequency alone, and has to be multiplied by a correction factor which depends on the width and shape of the line profile. For a gaussian profile with a dispersion $\sigma = 1000$ km/sec this correction factor is about 2 if the signal frequency is in the centre of the profile. The correction factor is roughly proportional to the dispersion and the mean brightness temperature for the central 0.25 square degrees of the cluster is found to be

$$T_b = (-0.06 \pm 0.14)\,\sigma\,10^{-3}\,^\circ\mathrm{K} \qquad (6)$$

for σ larger than 500 (expressed in km/sec). The upper limit for the mean brightness temperature may thus be set equal to

$$T_b = 0.14\,\sigma\,10^{-3}\,^\circ\mathrm{K}. \quad (\sigma \text{ in km/sec}) \qquad (7)$$

We now use this result to derive an upper limit for the number of neutral hydrogen atoms in a column of 1 cm² cross-section, assuming the gas to be optically thin and to have a gaussian velocity distribution with a dispersion σ. Using equation (12) from *B.A.N.* No. 452 we find

$$N = 1.835\ T_b \Delta V\, 10^{18}, \qquad (8)$$

where ΔV is the width of the profile in km/sec, which for a gaussian distribution is equal to $\sigma\ (2\pi)^{\frac{1}{2}}$. Inserting the value for T_b given above, we find for the upper limit

$$N = 6.4\,\sigma^2/10^{14}\ \mathrm{at/cm^2}. \qquad (9)$$

Assuming again $\sigma = 10^3$, we obtain

$$N = 6.4 \times 10^{20}\ \mathrm{at/cm^2}, \qquad (10)$$

or a neutral hydrogen mass of 1.1×10^{-3} g/cm².

The diameter of the field covered by our antenna beam is $0^\circ.57$ or 900 kpc if we use a distance of 89×10^6 pc for the Coma cluster, based on a value of HUBBLE's constant of 75 km/sec per 10^6 pc (SANDAGE 1958). The total mass of neutral hydrogen in the field is then less than

$$M_{\mathrm{H}} = 6 \times 10^{45}\,\mathrm{g} = 3 \times 10^{12} M_\odot. \qquad (11)$$

To obtain an estimate of the ratio of neutral hydrogen mass to total mass in the cluster we now calculate the mass of the visible galaxies in the same field of 0.25 square degrees, using the data given by OORT on this cluster (OORT 1958). From his data in Table 2, which are mainly based on counts by ZWICKY (1957), we find 136 bright nebulae (brighter than $16^m.5$) and 188 faint nebulae (between $16^m.5$ and $19^m.0$) in the field. Using an average mass-to-light ratio of 50 for these galaxies, OORT finds mean masses of 6×10^{11} and $0.5 \times 10^{11}\ M_\odot$ for the bright and faint galaxies. The total mass integrated over the field is then 9×10^{13} solar masses; the uncertainty is estimated to be not more than a factor of 2.

According to OORT's analysis there seems to be little mass in addition to that contained in the bright galaxies, with the mass-to-light ratio assumed. We may thus conclude that the ratio of neutral hydrogen mass to total mass in a field of 0.25 square degrees at the centre of the cluster is less than 0.03 if the assumed velocity distribution of the hydrogen is correct. A more general result is that this ratio is less than $0.03\ \sigma^2\ 10^{-6}$, with σ in km/sec.

If we assume the hydrogen to be solely associated with the individual galaxies and mainly present as interstellar hydrogen, the assumed velocity distribution will be approximately correct. The result that the average ratio of hydrogen to total mass for the individual galaxies is less than 0.03 is in agreement with the ratios obtained for some near-by extragalactic systems (VAN DE HULST 1958). Most of the galaxies in the Coma cluster are of types E or So, for which we would expect the ratio of hydrogen to total mass to be less than 0.01.

There is no observational evidence for the presence of neutral hydrogen as intergalactic gas in the cluster. ZWICKY (1957) has presented some arguments for the presence of intergalactic dark matter in clusters and points out the presence of unresolved intergalactic luminous matter, and the existence of luminous bridges between cluster galaxies. SPITZER and BAADE (1951) have suggested that all gas and dust originally present in the galaxies in the centre of the Coma cluster have been swept out of them by frequent collisions between the galaxies. Though the recent revision of the distance scale has reduced the collision rate considerably (BURBIDGE 1958) this picture seems still valid, and it is expected by BURBIDGE that a considerable amount of material which has been swept out is still present in the form of intergalactic gas and dust clouds, though it will partly have recondensed to form young galaxies. If we assume the neutral hydrogen to exist as intergalactic gas clouds having approximately the same velocity distribution and to be mainly present in the central part of the cluster, which has a width of about 20′ or 500 kpc, we find that the mean density of neutral hydrogen is less than 4×10^{-4} at/cm^3. If we assume a wider spatial distribution the density is still lower. We may conclude from our observations that the total amount of neutral hydrogen if present in the form of intergalactic gas is less than a few percent of the total mass.

Acknowledgement

The author wishes to express his sincere thanks to Mr A. C. HIN, who designed and adjusted the various special receiver parts needed for this experiment and who did most of the observing.

The investigation was made possible by the financial support from the Netherlands Organization for Pure Research (Z.W.O.).

REFERENCES

G. R. BURBIDGE 1958, *Ap.J.* **128**, 1.
D. S. HEESCHEN 1956, *Ap.J.* **124**, 660.
H. C. VAN DE HULST 1958, *Rapport 11e Conseil de Physique Solvay*, 219.
H. C. VAN DE HULST, C. A. MULLER and J. H. OORT 1954, *B.A.N.* **12**, 117 (No. 452).
H. C. VAN DE HULST, E. RAIMOND and H. VAN WOERDEN 1957, *B.A.N.* **14**, 1 (No. 480).
M. L. HUMASON, N. U. MAYALL and A. R. SANDAGE 1956, *A.J.* **61**, 97 (Table XII).
C. A. MULLER 1956, *Philips Techn. Rev.* **17**, 358.
C. A. MULLER 1959, *Symp. I.A.U.* **9**, 465.
C. A. MULLER and G. WESTERHOUT 1957, *B.A.N.* **13**, 151 (No. 475).
J. H. OORT 1958, *Rapport 11e Conseil de Physique Solvay*, 163.
A. R. SANDAGE 1958, *Ap.J.* **127**, 513.
M. SCHWARZSCHILD 1954, *A.J.* **59**, 273.
L. SPITZER and W. BAADE 1951, *Ap.J.* **113**, 413.
F. ZWICKY 1957, "Morphological Astronomy". Springer, Berlin.