21-CM HYDROGEN-LINE ABSORPTION IN THE SPECTRA OF DISCRETE SOURCES

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This paper is a short survey of the results obtained with the Dwingeloo 25-meter radio telescope (beamwidth 0°56) and the 21-cm receiver on hydrogen-line absorption effects in the spectra of a number of strong point sources. Earlier work on this subject has been done by Hagen, Lilley, and McClain [1], and by Davies and Williams [2]. Some preliminary results of the first part of the present investigation were already published [3].

1. GENERAL METHOD

The hydrogen-line profile observed with a radio telescope pointing at a discrete source may be considered to consist of two parts: (1) The *emission profile* due to all neutral-hydrogen clouds in the antenna beam which would be measured in the absence of the source; this profile we shall call "the expected profile" following Hagen, Lilley, and McClain. (2) The *absorption profile* due to the absorption of the continuous radiation of the discrete source by hydrogen clouds lying between the source and the telescope; this profile we will call "the true absorption profile." Since usually the width of the source is much smaller than the beamwidth of the telescope the expected profile is mainly determined by clouds or parts of clouds within the antenna beam but not in front of the source; while the source's possible absorption of hydrogen radiation from clouds behind it can be neglected.

Assuming a uniform hydrogen distribution over the solid angle of the source, we may write for the observed profile:

$$T_{\text{obs}}(\nu) = T_{\text{exp}}(\nu) - T_a(1 - e^{-\tau(\nu)}) ,$$

where T_a is the observed antenna temperature due to the continuous radiation from the source outside the hydrogen-line frequencies, and $\tau(\nu)$ is the optical depth of the neutral hydrogen in front of the source. The true absorption spectrum is given by the term $T_a e^{-\tau(\nu)}$, while the term $-T_a$ is introduced by the comparison method used in the receiver.

To obtain the true absorption profile and from it the optical depth of the hydrogen clouds we must find the expected profile and subtract it from the observed profile. Though it is impossible to determine the expected profile, in principle we can obtain a good approximation from measuring the hydrogen radiation in the immediate neighborhood of the source. In earlier work this was done by using the mean of a number of profiles taken around the source. We have tried to improve on this method by using constant-declination or constant-galactic-latitude scans [3] across the source at a large number of frequencies to derive the expected profile. The main reason for using this method was that in several cases large differences in slope of the intensity-versus-declination (or galactic-latitude) curves were found to occur on both sides of the absorption dip in the curve, which would lead to an incorrect expected profile when taking the simple mean of profiles on both sides of the source. Constant-declination scans were used in the cases of Cassiopeia A, Taurus A, and Orion A, while for Cygnus A and Sagittarius A constant-galactic-latitude scans were chosen. In the case of Virgo A, comparison measurements on a number of surrounding points were made in the same way as the observations for M 31 were made by van de Hulst, Raimond, and van Woerden [4].

Figs. 1 to 5 give the measured profile and the expected profile, together with the true absorption profile derived from these two by subtraction. All the observed profiles were taken with a receiver bandwidth of 5 kc/s, corresponding to 1 km/second, while the scans and comparison profile were taken with a bandwidth of 10 kc/s, because the expected profile does not show the fine structure of the absorption profile and thus could be measured with a somewhat wider beamwidth with the advantage of smaller noise fluctuations. The r.m.s. noise fluctuation on the mean observed profile is about 1 °K and slightly larger for the expected profile in most cases.

2. INDIVIDUAL SOURCES

Cassiopeia A: A profile taken with a 10-kc/s beamwidth has already been published [3]. New 5-kc/s observations confirm the earlier results and reveal one more component on the low-frequency slope of the strong line at −38 km/second. A total of eight components have now been found: four due to absorption in the Orion arm and four due to the Perseus arm. The absorption in the latter arm is stronger than in the first, with optical depths to 3 or 4, while in the Orion arm the absorption is less than 2. This is the only available case of absorption in the Perseus arm. Of interest are the three components with optical depth less than 0.1 in the Orion arm.

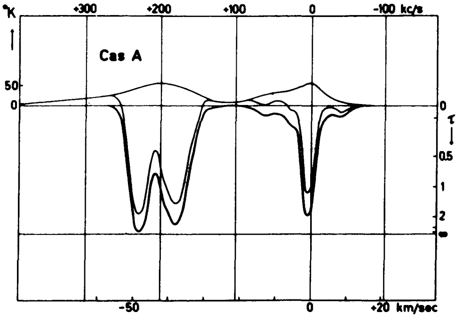

FIG. 1. Absorption profile of Cas A. The temperature indications in Figs. 1 through 5 are antenna temperatures, and are smaller than the brightness temperatures used in other Dutch papers by approximately 30 per cent. *Upper curve*: expected profile; *middle curve*: observed profile; *lower curve*: true absorption profile.

A comparison with theoretical gaussian profiles generally gives a very good agreement, though the tails extend somewhat farther out than a gaussian profile. The same effect of a slightly wider tail was found in the spectra of other sources where a separation of the spectra into individual components made the assump-

https://doi.org/10.1017/S0074180900051159 Published online by Cambridge University Press

tion of a somewhat wider, more or less exponential tail necessary to obtain a good agreement with the measured spectra. It is, however, a small deviation occurring mainly in the part of the profile where $\tau < 0.2\tau_{\max}$. Further investigation of this effect is necessary.

The absorption spectrum of Cassiopeia A places the source in but not beyond the Perseus arm. This is in agreement with the newest optical observations of the source [5], which place it at a distance of 3.4 kiloparsecs.

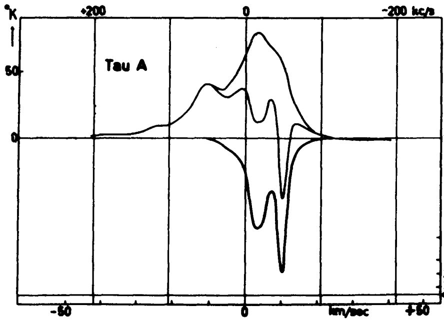

FIG. 2. Absorption profile of Tau A.

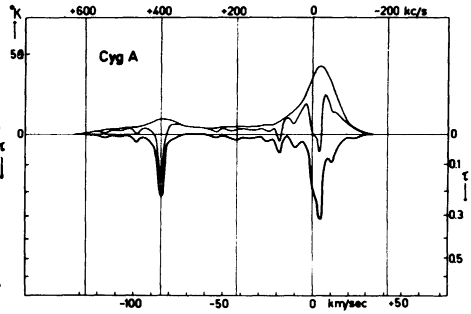

FIG. 3. Absorption profile of Cyg A.

Taurus A: Absorption occurs over part of the profile only. There is one narrow line of optical depth 1.9, which has a width corresponding to a cloud temperature of merely 125 °K, assuming a purely thermal widening of the line with a gaussian distribution. The second strong line shows definitely a flat top. Since this cannot be explained by saturation, one possible explanation is that the line is a blend of two equal components 1.0 km/second apart, and has a width that corresponds to a velocity distribution of 1.4 km/second r.m.s. and a depth of 0.6. A fourth component shows up on the slope of this wide line. No absorption occurs in the negative velocity wing and tail of the emission profile, which places the corresponding clouds beyond the source.

Cygnus A: The spectrum shows a large number of lines of small optical depth. At least eight components are visible. There seem to be some other lines of very small optical depth, less than 0.02, but more observations are necessary to ensure their reality. In the third arm there is a clear absorption in agreement with the identification of Cygnus A as an extragalactic object. The constant-galactic-latitude scans show that Cygnus A lies just outside the high-intensity Cygnus region, which probably explains the low intensity and low optical depth.

Orion A: The absorption spectrum shows only one broad line of optical depth 1.4 and a width of 2.4 km/second at 4 km/second. The profile obtained is somewhat asymmetric, which may be caused by a small error in the present expected profile. If it is real, then the line is actually a blend.

Virgo A: This source lies near the galactic pole and a very low optical

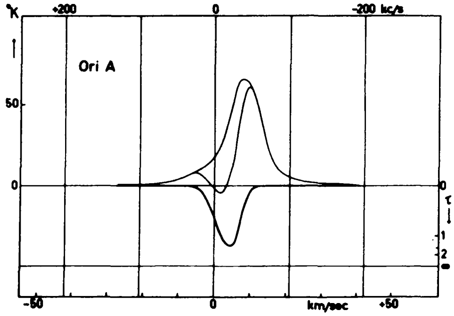

FIG. 4. Absorption profile of Ori A. *Upper curve*: expected profile; *middle curve*: observed profile; *lower curve*: true profile.

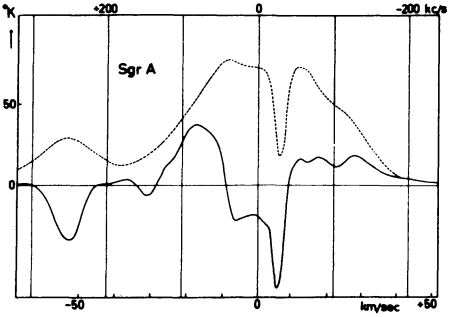

FIG. 5. Absorption profile of Sgr A. Only the central-frequency range is given; the expected profile (*dotted curve*) is provisional.

depth was expected. The observed profile has a maximum intensity of only 5 °K and does not show any clear absorption dips. It was found impossible to determine a reliable expected profile, mainly because of the large difference in received intensity between points in the immediate neighborhood of the source. Some points 1 degree away from the source show intensities of more than 10 °K, while others show about the same intensity of 5 °K. Measurements were made on 12 comparison points around the source at a number of frequencies, around the maximum of the observed profile. About three-quarters of these measurements show a lower intensity of the source, which may mean that there is some absorption present.

Sagittarius A: Only the part from −200 to +200 kc/s has been studied in the present investigation. Rougoor [6] gives the results of the absorption in the low-intensity wings. Right now only some preliminary results can be given because the expected profile is not final, and the material is not yet complete. Absorption occurs over the main part of the profile in contrast to the earlier results by Hagen, Lilley, and McClain [1]. Our present knowledge about the expansion effects in the central part of our Galaxy does not seem to contradict the assumption that the source is at the center. The optical depth in the central part of the profile is large and seems to be greater than two at least. The analysis is complicated by the self-absorption effects in the expected and the other profiles in this region, and by the fact that the source itself is a singular point in the galactic system, its width comparable to the antenna beamwidth. No separation into individual components has yet been tried.

3. CONCLUSION

Table I summarizes the results for the first four sources. For Cassiopeia A the preliminary results [3] are quoted, while the eighth component is only indicated. The last column gives the total number of neutral hydrogen atoms along a cylindrical column of 1 cm^2 assuming a cloud temperature of 125 °K. In general the r.m.s. velocity of the clouds is larger rather than corresponding to 125 °K (1.0 km/second) since it ranges from 1.0 to 2.6 km/second, but it is probable that part of this velocity is a result of nonthermal mass motions in the clouds.

TABLE I

ABSORPTION COMPONENTS IN FOUR BRIGHT SOURCES

Source	Radial Velocity km/second	Max. Optical Depth	R.m.s. Velocity km/second	N atoms/cm²
Cas A	+ 7.6	0.08	2.0	0.9×10^{20}
	− 0.8	1.85	1.5	16
	− 6.6	0.09	1.9	1.0
	− 12.5	0.07	2.6	1.0
	− 30			
	− 38.1	2.6	2.5	38
	− 42	0.3	2.3	5.2
	− 48.2	4	1.8	41
Tau A	+ 10.3	1.9	1.0	11
	+ 3.9	0.6	1.4	5.0
	+ 2.9	0.6	1.4	5.0
	− 4	0.07	1.7	0.7
Cyg A	+ 10.6	0.09	2.5	1.3
	+ 3.8	0.26	1.6	2.4
	0	0.16	1.9	1.7
	− 9.5	0.04	2.1	0.5
	− 18.3	0.06	1.5	0.5
	− 25.3	0.02	2.1	0.2
	− 84.5	0.22	1.5	1.9
	−100.5	0.02	1.6	0.2
Ori A	+ 4	1.4	2.4	19

REFERENCES

[1] Hagen, J. P., Lilley, A. E., and McClain, E. F. *Radio Astronomy* (I.A.U. Symposium No. 4, 1955). Cambridge, England, 1957, p. 80.
[2] Davies, R. D., and Williams, D. R. W. *Radio Astronomy* (I.A.U. Symposium No. 4), p. 71.
[3] Muller, C. A. *Ap. J.* **125**, 830, 1957.
[4] van de Hulst, H. C., Raimond, E., and van Woerden, H. *B.A.N.* **14**, 1, 1957.
[5] Minkowski, R. Paper 61.
[6] Rougoor, G. W., and Oort, J. H. Paper 77.

Discussion

Westerhout: The cool foreground cloud in the central region was discovered way back in 1953 by Heeschen at Harvard.

Conway: Since Mr. Muller's optical depth in hydrogen is about 4 at the line center, is Mr. Adgie not being unduly pessimistic in taking the hydrogen optical depth as 1.25?

https://doi.org/10.1017/S0074180900051159 Published online by Cambridge University Press

Adgie: My band was approximately gaussian and had a width about equal to the major absorption profile (i.e., 18 kc/s). The deep profile at 21 cm at $\tau = 4$ is fairly narrow and is diluted in my bandwidth. If this deep line is looked for with a narrow bandwidth the receiver sensitivity is reduced and the over-all signal-to-noise ratio will probably not be increased by any appreciable extent.

Oort: I noticed that in your Cygnus A profile there was a part in which the expected profile showed emission but no absorption. This seems impossible, as all galactic hydrogen must be situated between Cygnus A and us. The effect must therefore be due to uncertainty in the expected profile.

Muller: It just may be, that in this small range no clouds lie over the source.

Heeschen: Do your observations indicate that all or most of the interstellar H I in the direction of Cygnus A is concentrated in discrete clouds, and if so can you from these absorption observations get some idea as to the distribution of interstellar clouds?

Muller: No further analysis has yet been made owing to lack of time before the symposium.