

REPORT ON 21-CM. OBSERVATIONS
BETWEEN $l=60^\circ$ AND $l=135^\circ$

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Observations of the 21-cm. hydrogen profiles have been taken between galactic longitudes $l=60^\circ$ and $l=135^\circ$, with the 24-ft. radio telescope at the George R. Agassiz Station. The beam-width of the antenna is approximately $1^\circ.7$ between the half-power points. The electronic equipment used was a d.c. comparison radiometer, which has a signal channel with a frequency band-width of 15 kc./s. between the half-power points. At galactic latitude $b=0^\circ$ the observations are generally spaced $2^\circ.5$ apart, although a few gaps of 5° exist. At $b=+15^\circ$ and $b=-15^\circ$ the centres are 5° apart. A strip in latitude at $l=100^\circ$, and other centres at various latitudes (mainly at $l=75^\circ$ and $l=87^\circ.5$) have also been taken, but little reference will be made to this material in the present paper.

I. SPIRAL STRUCTURE IN THE GALACTIC PLANE

One of the most striking features on all the scans is the abundance of small details. Each large maximum (a spiral arm) has superimposed on it several of these. See, for example, the reduced profiles for the regions shown in Figs. 2, 3 and 5. Unfortunately, many of these details are near the limit of detectability of the equipment so that little can be said about them. Their appearance, however, agrees with observations of the optical interstellar lines, which are multiple for stars in both the Orion and Perseus arms.

A preliminary report giving the general features of spiral structure in the galactic plane has been published (Matthews [1]). Fig. 1 has been taken from that article. The velocities of the larger details in the galactic plane have been plotted against galactic longitude, and lines have been drawn to indicate how the details might run. These lines suggest that the details are continuous from one region to the next. This is probably true for the Orion arm, but for the Perseus and Distant arms the lines

indicate, rather, the general trends of the various large details. There is a satisfying agreement between this and a similar plot made by Westerhout [2]. The few differences will probably be resolved when the reductions now in progress have been completed. The plot in Fig. 1 is still preliminary, and a final result will have to await complete reduction of all the observations, in a manner which will be suggested below. The analysis now in progress gives evidence that the final plot will be more detailed, and that many of the features do, indeed, occur over large intervals of longitude, even for the more distant arms.

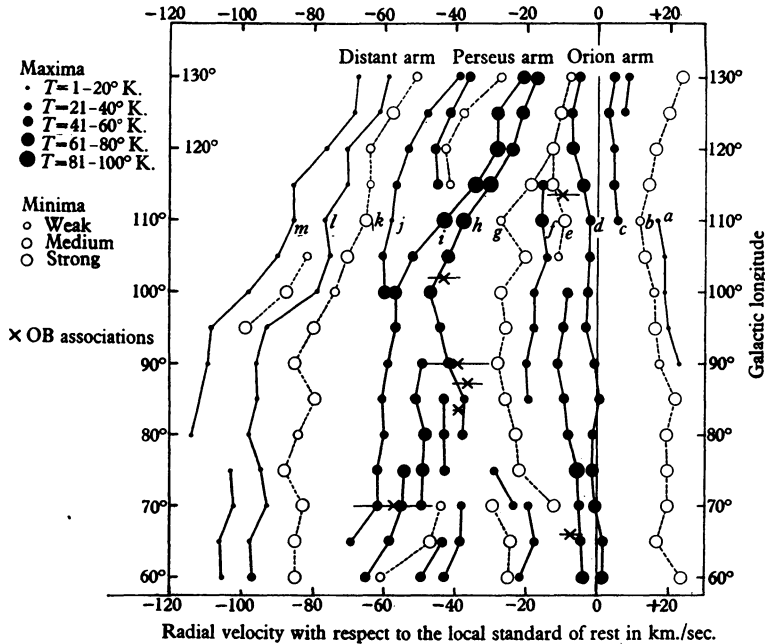


Fig. 1. 21-cm. observations of hydrogen in the galactic plane. The velocities of the larger details in the galactic plane, both maxima and minima, are plotted as a function of longitude. Lines have been drawn to suggest how the features change with longitude. The velocities of seven OB associations, deduced from the observed radial velocities, are also plotted together with their probable errors.

Little can be said now from these observations about the tilt of the spiral arms, or about their structure away from the plane, although both subjects are of great interest, as has been shown by Helfer and Tatal [3] and by Westerhout [4]. The observations for low galactic latitudes at $l = 100^\circ$ are being reduced now and will be ready for discussion shortly. Further observations have been taken this summer at the Agassiz Station by Mr R. J. Davis to investigate these problems between $l = 110^\circ$ and $l = 130^\circ$.

Two features of Fig. 1 are of particular interest. The first is a branch of the Orion arm, which has definitely separated from the main arm to more negative velocities at $l = 100^\circ$, and can be traced to smaller longitudes. This branching has already been noted by Oort, van de Hulst and Muller [5] and corresponds closely to the distribution of OB aggregates as given by Morgan, Whitford and Code [6]. The branch does not stop at $l = 115^\circ$ as the diagram suggests. [Observations above the plane show that it continues there to at least $l = 130^\circ$. The line of maxima which runs from $l = 60^\circ$ to $l = 100^\circ$ at velocities between -4 km./sec. and -12 km./sec. seems to be due to the pronounced maxima at these velocities, which occurs at latitudes near $b = +5^\circ$ in this longitude interval according to Helfer and Tatel [3].

The second interesting feature is the double line of maxima that either branches off from the negative velocity side of the Perseus arm as suggested by Fig. 1, or arises near the arm as suggested by Westerhout [2]. It first becomes distinct near $l = 110^\circ$. If the observed velocities of this arm, or branch of an arm, are interpreted as being due to distance, then we find that it is inclined at an angle of about 25° to the radius vector from the galactic centre. This assumes that the hydrogen has no systematic velocity, and explains the observed velocities through galactic rotation. Its slope will be greatly modified, however, if the hydrogen possesses any peculiar radial motion with respect to the local standard of rest, since the effects of galactic rotation are rapidly decreasing to zero for longitudes greater than 110° . It is interesting to note that the velocities of this line of maxima are, for successive longitudes, closely parallel to those of the Perseus arm, but shifted by about -20 km./sec. If we may assume that the hydrogen giving rise to this feature has the large peculiar velocity of -20 km./sec., then it is at the same distance as the Perseus arm over the interval from $l = 115^\circ$ to $l = 135^\circ$, and possibly to even greater longitudes according to Westerhout's plot (Westerhout [2]). If the latter assumption is correct, we have the case of a large mass of hydrogen moving with a considerable peculiar velocity, whereas the only other direct evidence for large peculiar motions pertains to small masses of hydrogen having positive velocities. Since velocities if due to galactic rotation are negative in this longitude interval, all points in Fig. 1 with positive velocities must be due to hydrogen having a systematic velocity of recession. The large positive velocities shown in the diagram refer to very small amounts of hydrogen, while the small positive velocities are associated with larger masses of hydrogen. This is in general agreement with the results for optical interstellar lines (Whipple [7]; Blaauw [8]).

2. FINE STRUCTURE OF THE 21-CM. PROFILES

All the analysis of these observations that has been carried out shows that the profile of a spiral arm is usually made up of more than one significant part. Many of the scans show several very obvious maxima; for example, the profile for the Orion arm at $l = 114^\circ$, $b = +4^\circ$ (Fig. 3) shows two well-separated, approximately equal, maxima. The same profile also shows several definite, but less pronounced, details: one between the Perseus and Orion arms, and several more at higher negative velocities. These details

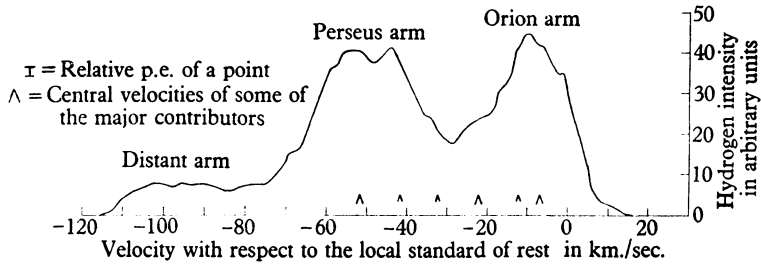


Fig. 2. The mean profile for $l = 97^\circ$, $b = -1^\circ$ (LF 5). The relative probable error indicated is the probable error of one point relative to another point 3 km./sec. away. The inverted V's indicate the central velocities of the Gaussian curves used to analyze the observed profile.

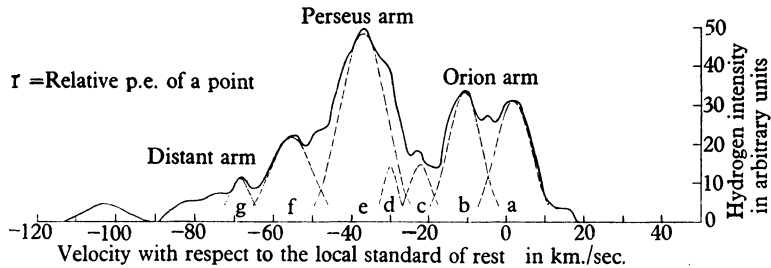


Fig. 3. The mean profile for $l = 114^\circ$, $b = +4^\circ$ (LF 6). The analysis of this profile has been made according to the method described in Section 2.

repeat on profiles taken several months apart, and similar details are found on scans for centres five or more degrees away. The velocities of the details may differ by two or three km./sec. in two regions that are close together, and the intensities may be somewhat different in the two regions: but the similarity in appearance of the details, together with the small change in velocity, often make their common origin probable. Details such as these suggest that the frequency band-width used (15 kc./s. between the half-power points, which is equivalent to 3.2 km./sec.) is small enough to show real details of structure in the hydrogen. The fine details are by no means fully revealed on profiles taken with a 15 kc./s. band-width; this is clearly demonstrated by Fig. 4.

The 5 kc./s. band-width profile is taken from the only pair of scans obtained with the present Harvard equipment using the narrow band-width. Additional observations should be taken to check the detailed features of the profile. This will be possible with the new equipment under construction.

To assess the reality of the individual features in the 5 kc./s. band-width profile of Fig. 4, the average probable error of the difference in intensity between points a band-width apart was computed from the differences between the two scans that form the mean profile. The average probable error for a point computed in this manner is ± 0.53 units for the 5 kc./s.

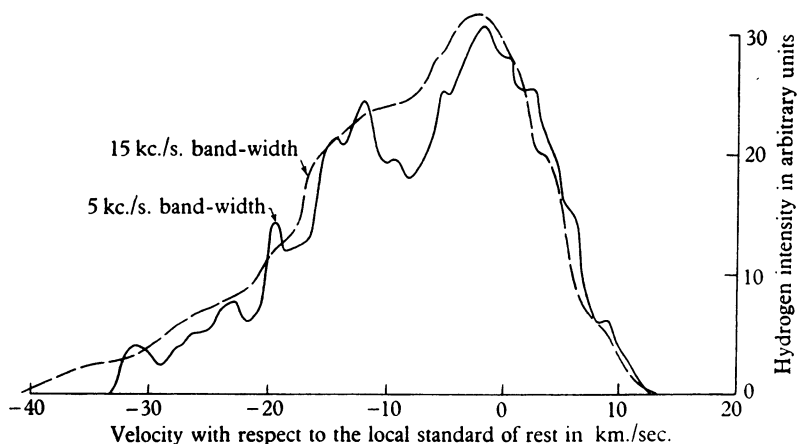


Fig. 4. Mean profiles for $l=100^\circ$, $b=+15^\circ$. The dashed-line profile is the mean of two pairs of scans taken with a 15 kc./s. receiver band-width at the half-power points. The solid-line profile is the mean of one pair of scans taken with a 5 kc./s. band-width. There is an uncertainty of about 5% in the factors used to reduce the pairs of scans to a common intensity scale.

band-width profile, and ± 0.52 units for the 15 kc./s. band-width profile. The low value for the 5 kc./s. band-width profile was secured mainly because its scans were taken with an integration time four times that used for the 15 kc./s. band-width scans.

The reality of each of the individual features on the 5 kc./s. band-width profile was evaluated from a consideration of the mean profile and the probable error of a point, and also from the agreement between the original scans in each feature. The evaluation shows: that the features at $V_{LSR} = +2.5, -2.0, -12.0, -14.5, -19.5, -23.0$ are definitely real; that those at $V_{LSR} = +8.5, +6.0, +0.5, -9.5, -31.0$ are probably real; and that those at $V_{LSR} = +4.5, -5.5, -27.0$ are of doubtful reality.

Yet another piece of corroborative evidence for the fine structure is

given by the observations of optical interstellar lines. Dr G. Münch has very kindly given the author the results of his observations on interstellar sodium and calcium lines for fourteen stars between $l=90^\circ$ and $l=106^\circ$. Adams[9] has observed one star in this region. All these observations are from stellar spectra having dispersions greater than $5 \text{ \AA}/\text{mm}$. Sixteen of the lines which are present in the spectra of these stars are due to clouds in the Orion arm. Their velocities with respect to the local standard of rest are mostly between -2.5 km./sec. and -6.5 km./sec. , with a few velocities outside this range. The computed standard deviation for all sixteen lines is 3.6 km./sec. ; the value of σ is strongly influenced by one discordant velocity.

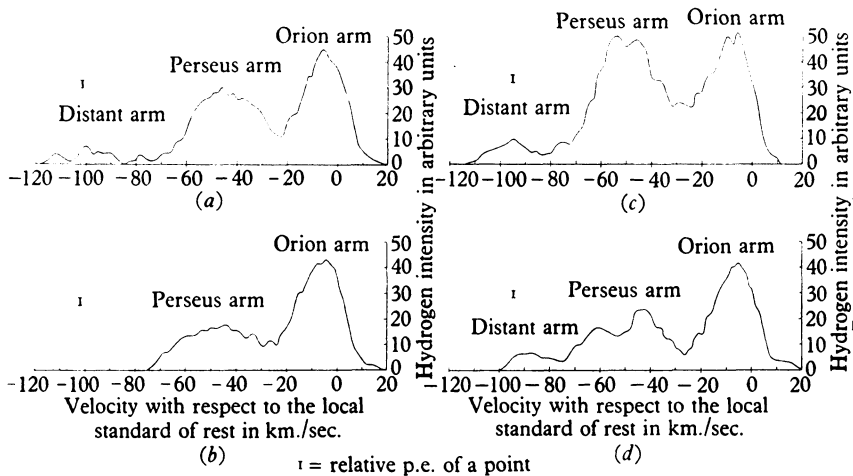


Fig. 5. (a) The mean profile for $l=102.6^\circ$, $b=-2.7^\circ$. (b) The mean profile for $l=102.6^\circ$, $b=-3.8^\circ$. These two profiles include the region of the h and χ Persei clusters. (c) The mean profile for $l=100.0^\circ$, $b=-2.1^\circ$. (d) The mean profile for $l=99.9^\circ$, $b=-4.2^\circ$.

If the broadest reasonable gaussian curve is used to represent the Orion arm both at $l=97.0^\circ$, $b=-1.3^\circ$ (LF 5, Fig. 2) and at $l=102.6^\circ$, $b=-2.7^\circ$ (Fig. 5a), which are representative curves for the longitude interval between 95° and 106° , we find that the values of σ are 7.1 km./sec. and 7.0 km./sec. respectively. One might expect that the values of σ from the optical and radio data would be approximately equal. If we assume that at least one of the main contributors to the 21-cm. profile has a dispersion of about 3 km./sec. , then the analysis of the Orion arm profiles for these two regions is greatly altered. The small, but not insignificant, contributors which were needed when a $\sigma=7 \text{ km./sec.}$ was used become much more prominent. The Orion arm is now composed of three roughly equal components.

The velocities of the optical interstellar lines in the spectra of stars included in the antenna beam pattern generally agree quite well with the velocities of the maximum of the Orion arm profile, or with some of the more prominent fine details. This is particularly true for the clouds in the Orion arm since both types of observations refer to the integrated effect of the whole arm.

Dr Münch^[10] has pointed out that the optical interstellar lines for the Perseus arm, which are well separated from the components belonging to the Orion arm, are very complex at longitudes 85° and $102^\circ.5$. The observed velocities occur over the whole velocity interval covered by the 21-cm. profile of the arm (see also van de Hulst, Muller and Oort^[11]). The stars observed by Münch around $l=102^\circ.5$ are all members of the h and χ Persei clusters. Although the exact location of the double cluster in the Perseus arm is still unknown, it is probable that the observed spread of velocities in the optical interstellar lines can be attributed to random motions of the clouds of the order of 10 km./sec. If so, these random velocities would explain the featureless character of the 21-cm. profiles for the Perseus arm at the position of the h and χ Persei clusters. The profiles are shown in Figs. 5*a* and 5*b*, and can be compared with the profiles at $l=100^\circ$ given in Figs. 5*c* and 5*d*.

A comparison between all the available profiles at $l=100^\circ$ and those at $l=102^\circ.5$ (many more than are shown in Fig. 5) shows that the variation with latitude is quite similar at the two longitudes for (a) the maximum intensity of the Perseus arm, (b) the intensity at $V_{LSR} = -39$ km./sec., which is the velocity of the h and χ Persei clusters, and (c) the total area under the profile of the Perseus arm. These facts indicate that the h and χ Persei clusters have at present only a very slight influence on the gross characteristics of the neutral hydrogen in the Perseus arm. The absence of any H II region near the double cluster (Shajn and Hase^[12]) further strengthens this belief.

An examination of the Orion arm profiles in Fig. 5 shows how the fine details persist, and also change, over a limited region. The persistence of these details, and the manner in which they change, over an area of the sky, coupled with the foregoing discussion, suggest that it is not out of order to consider the observed 21-cm. profiles as the sum of a limited number of simple gaussian curves. Each gaussian curve can be considered as being produced by a hydrogen 'cloud' or grouping of 'clouds'. The maximum intensity and dispersion of each gaussian curve is determined by fitting their sum to the observed profile.

It is important to remember that the true curves for an individual

hydrogen 'cloud' may not be gaussian, and they may well be asymmetrical. For a first attempt, however, we may make the foregoing assumptions and see if the results are reasonable. The profile for LF 6 has been analyzed in this manner and the results for the larger details are indicated in Fig. 3. The Orion arm can be almost completely represented by two such curves, as indeed the original profile itself suggests; for curve (a), $\sigma = 4.6$ km./sec., for curve (b), $\sigma = 4.3$ km./sec. The small detail between the two maxima in the Orion arm seems to be almost negligible. Several small details on or near the profile of the Perseus arm appear, however, to have more importance. The profile for the Perseus arm is more difficult to analyze. It can be represented rather well by one major contributor having a $\sigma = 5.9$ km./sec., with two or three much smaller components.

The quality of performance of the equipment necessary to obtain the observations discussed in this paper was due mainly to the efforts of Mr J. C. Campbell.

REFERENCES

- [1] Matthews, T. A. *P.A.S.P.* **67**, 112, 1955.
- [2] Westerhout, G. Unpublished communication, 1955.
- [3] Helfer, H. L. and Tatel, H. E. *Ap. J.* **121**, 585, 1955.
Helfer, H. L. and Tatel, H. E. Paper read at the Princeton Meeting of the A.A.S., 1955.
- [4] Westerhout, G. This symposium publication, paper 5.
- [5] Oort, J. H., van de Hulst, H. C. and Muller, C. A. *Kon. Nederl. Akad. Wetenschappen, Amsterdam*, **61**, no. 8, 1952.
- [6] Morgan, W. W., Whitford, A. E. and Code, A. D. *Ap. J.* **118**, 318, 1953.
- [7] Whipple, F. L. Centennial Symposia (*Harvard Obs. Mono.* no. 7), p. 109, 1948.
- [8] Blaauw, A. *B.A.N.* **11**, 459, no. 436, 1952.
- [9] Adams, W. S. *Ap. J.* **109**, 354, 1949.
- [10] Münch, G. *P.A.S.P.* **65**, 179, 1952.
- [11] van de Hulst, H. C., Muller, C. A. and Oort, J. H. *B.A.N.* **12**, 117, 1954.
- [12] Shajn, G. A. and Hase, V. F. *Pub. Crimean Astrophysical Observatory*, **10**, 152, 1953.

Discussion

Westerhout: The situation in Matthews' Fig. 1 near $l = 80^\circ$, where he finds four different details in the Perseus arm running closely parallel, may be explained from the Leiden observations. There it is shown that at $l = 75^\circ$, $b = +2^\circ$ a branch with higher negative velocity branches off from the Perseus arm and runs parallel to it until it joins up again at $l = 85$, $b = +2.5^\circ$. Parts of this positive-latitude arm stick through the plane $b = 0$ at several places and give rise to the great number of little maxima found by Matthews.

From the Leiden observations it is also clear, that a series of maxima that occurs at the negative-velocity side of the Perseus arm near $l = 110^\circ$, if ascribed to galactic rotation, is due to a small extra arm which runs at a latitude of approximately $+2^\circ$.