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A 21-CM. STUDY OF THE ORION REGION

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An analysis of the profiles of the 21-cm. radiation from neutral hydrogen promises to be of great importance for a study of the internal motions of specific regions of the Galaxy. The two factors which influence the shape of the profiles are the velocity distribution and the density distribution of the neutral hydrogen atoms in the line of sight. The velocity distribution is essentially determined by three factors (1) galactic rotation, (2) the random motions of the gases, and (3) local peculiar motions as, for example, expansion. In the plane of the Galaxy in any specific direction the isolation of a region of particular interest is made difficult because of the superposition of the radiation along the entire line of sight. Hence regions at intermediate galactic latitudes are more suitable for study of internal motions than regions on or near the galactic equator. Also, for the study of peculiar motions, regions with small galactic rotation terms have the distinct advantage that any prevailing preferential motion will be clearly indicated by the profiles. The Orion region satisfies most of the above requirements. The galactic latitude of the section under consideration falls between -10° and -25°, and at the mean galactic longitude of 170° the galactic rotation term in radial velocity amounts to 7 km./sec. at a distance of 500 parsecs. Moreover the Orion region contains many features of considerable interest like the Orion Nebula, the Orion Association, the great arc of ionized hydrogen and many smaller H II regions. The great arc of Barnard (1895) [1] forms part of an almost elliptical ring of emission nebulosity with dimensions $14 \times 12^\circ$. At the distance of 500 parsecs for the Orion Association these dimensions are of the order of 120×105 parsecs. It is of interest to note that the major axis of this ellipse is parallel to the galactic equator. This ellipticity could presumably be caused by galactic rotation, by a galactic magnetic field with lines of force along the spiral arms, or by the rotation of the whole mass itself. Further investigation is necessary to decide which of the above effects is most important.

1. OPTICAL PROPERTIES OF THE ORION REGION

Observations of interstellar absorption lines for about forty stars of the Orion region are included in Adams' list (1949) [2]. This list gives radial velocities and the intensities of the components of the H and K lines of calcium. Most of the O and B stars in Adams' list for the Orion region are relatively nearby. Upon close examination of the velocities of the interstellar components, one is struck by the considerable number of components with excessive negative velocities. This fact was recognized early by Sanford and Adams. Later Whipple (1948) [3], Blaauw (1952) [4], and Schlüter, Schmidt and Stumpff (1953) [5] have also commented on this anomaly. Whipple (1948) in his analysis of Adams' data (in an attempt to find evidence for the cloud structure of the interstellar medium) grouped components with about the same velocities in stars close together in the sky and assumed that those components are produced by the same cloud. This is an extremely simplified model. For example, of the two stars θ^1 Orionis and Bond 619 which are less than $3'$ apart, θ^1 Orionis has four interstellar components with velocities $-15{\cdot}5$, $-5{\cdot}8$, $+0{\cdot}5$, $+11{\cdot}9$ km./sec. and intensities 2, (?), 3, 4 respectively, whereas Bond 619 has only one interstellar component with a velocity of $+2$ km./sec. and intensity 4b. In the majority of stars the strongest interstellar component has a positive radial velocity while the faintest one has generally the largest negative velocity. Also, Adams found that almost invariably the strongest component of a complex line is the one which corresponds to pure galactic rotation. This fact, combined with the anomaly noted above, seems to suggest that the components with excessive negative velocities may be produced close to the individual stars and hence have a distinctly different origin from the strong positive components. This would be the case if the negative velocity components were formed near the boundary regions of the Strömgren spheres of the individual stars—a conclusion which is strongly supported by the work of Schlüter, Schmidt and Stumpff (1953) [5], who have plotted the distribution of early type stars and the distribution of large negative velocity components. Recent theoretical studies by Oort (1954) [6] and by Spitzer and Oort (1955) [7] furnish a mechanism for acceleration of interstellar clouds in such boundary regions.

The anomalous position of η Orionis has been pointed out by Whipple (1948) [3] and Adams (1949) [2]. The spectrum of the star shows double interstellar H and K lines of unequal intensity. The stronger component, which has a negative velocity of $-10{\cdot}2$ km./sec., gives a large residual when corrected for galactic rotation very different from that for other stars of the same region; but the fainter component, which has a positive velocity of $+6{\cdot}8$ km./sec., gives an accordant value. This peculiarity of the region around η Orionis is reflected in the 21-cm. profiles as we shall show below.

Using Sharpless' (1954) [8] tabulation of early-type stars belonging to the Orion Association, a plot has been made of the distribution of stars earlier than B4 (Fig. 1). This diagram shows that practically all stars

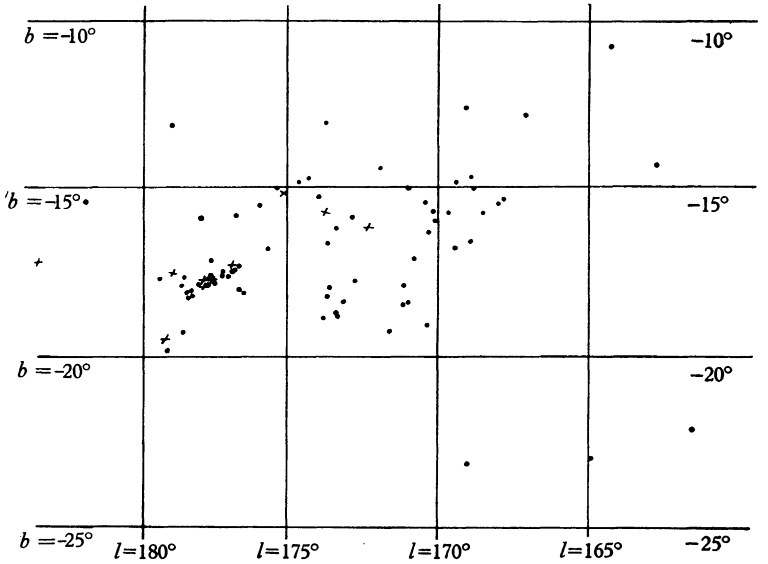

Fig. 1. Distribution of early-type stars in Orion. Crosses: O–B0 stars; dots: B1–B3 stars.

belonging to this group are distributed in a strip between $l = 166°$ to $l = 178°$ and $b = -19°$ to $b = -14°$. There are a dozen O–B0 stars, 16 B1 stars and 57 B2–B3 stars within this strip. We note that the Orion Association extends twice as far in galactic longitude as in latitude and hence it possesses a decidedly flattened shape (Pannekoek, 1929) [9].

2. THE 21-CM. OBSERVATIONS FOR THE ORION REGION

For a detailed study of the distribution of neutral hydrogen in the Orion region, profiles of the 21-cm. line were obtained at 3° intervals in galactic latitude and longitude for the region $l = 160°$ to 182° and $b = -25°$ to $-10°$. Fig. 2 shows the reduced profiles for most of the region. The velocities are with respect to the local standard of rest. The observations were made with the equipment of the G. R. Agassiz Station as described by Lilley (1955) [10], using a beam-width of 1°.7 and band-width of 15 kc./s. The profiles have not been corrected for band-width or random velocity. The band-width correction was found to be so small as to be negligible. The random velocity corrections were generally not made for the profiles since it was not certain what value of random velocity would be appropriate for any particular region under consideration. However, some of the profiles of particular interest were corrected for an assumed average random motion to study the effect of such a correction on the profiles.

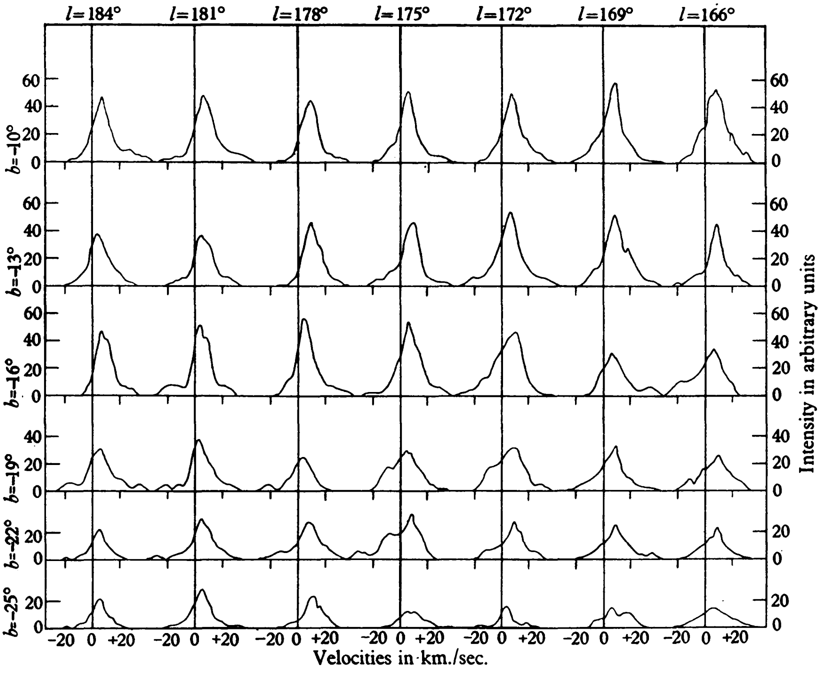

Fig. 2. Observed 21-cm. line profiles in the Orion region.

The most striking characteristic of the 21-cm. profiles of the Orion region is the rapid variation in the shape of the profiles from position to position. The profiles for positions north of $b = -16°$ are, in general, sharp with small irregularities in the wings.

The profiles for a region bounded by $l = 172°$ to $178°$; $b = -19°$ to $-22°$ show a marked asymmetry on the negative velocity side. If these profiles are corrected for random motions, assuming any reasonable value of the random velocity, the correction is such that the resultant profiles have two peaks, one on the negative velocity side and the other on the positive velocity side. The principal peaks of all the profiles show positive velocity. We note here that the galactic rotation effect for the Orion section is positive. Hence any subsidiary peak on the negative velocity side definitely indicates a real motion towards us and cannot be an effect of distribution of atoms along the line of sight. As pointed out earlier, the interstellar absorption lines for η Orionis ($l = 172°$, $b = -19°$) also indicate a strong negative component. This negative component is distinctly different from the excessive number of negative velocity components found in the region, since the latter are all weak in intensity. It is surprising to note that the region, where we have the maximum amount of hydrogen moving towards us, is comparatively free of emission nebulosities or early-type stars.

Maximum asymmetry is shown by the profiles for the section $l = 172°$ to $175°$; $b = -19°$ to $-22°$. Confining our attention to this small section, we can compute from the area of the profiles the total number of neutral hydrogen atoms along the line of sight in a cylindrical column 1 cm.^{2} in area. This value is of the order of $1 \cdot 7 \times 10^{21}$ atoms. Now, on the assumption that the whole contribution in the line of sight is from a column 100 parsecs in length we can derive the space density of neutral hydrogen atoms. This density proves to be of the order of 5 atoms/cm.^{3}. Before we can derive the total density, we must have an idea of the ionization equilibrium in the region. This is difficult because there are no reliable estimates of the emission measures for the region available. However, for the restricted region under consideration, H_α photographs show only extremely feeble emission. An order of magnitude check on the derived densities is obtained as follows: The star σ Orionis ($l = 174 \cdot 5°$, $b = -16°$) has one of the best defined associated Strömgren spheres. The diameter of the sphere is approximately 17 parsecs. Taking the value of $s_0 N_H^{\frac{2}{3}}$ for an O9·5 star from Strömgren's tables (1948) [11] we find that for the observed dimensions the value of N_H is of the order of 10 atoms/cm.^{3}. Considering the uncertainties in the data, the agreement is good. There are obviously local variations in density over the region, but 21-cm. observations combined with the above optical estimate indicates a well-established lower limit to the average density of about 5 atoms/cm.^{3} and a maximum average density of some three times this value.

For the restricted region considered above the total mass represented by the approaching portion of the profiles is found to be about 3200 solar masses for a region 26×26 parsecs and the comparable mass with positive velocity is about 6000 solar masses. These values represent only rough lower limits. The velocities of the positive and negative components are $+12$ km./sec. and -5 km./sec. with respect to the local standard of rest.

The galactic rotation effect is about 7 km./sec. for this region and, correcting the zero velocity line for this velocity, we find that the two peaks have velocities +5 km./sec. and −12 km./sec. respectively.

Before we consider the interpretation of these observations, there are a few further points of interest to be noted in the profiles. In photographs of this region (*Ross Atlas*, no. 34) it is seen that the absorption increases with decreasing galactic latitude. Along with this increase in absorption, the half-widths of the 21-cm. profiles decrease quite clearly. This is not surprising since the presence of any large amounts of dust within the gas may presumably inhibit to a certain extent any large-scale internal motions of the gas. In other parts of the Galaxy we have noted that the sharpest 21-cm. profiles are often associated with regions of high local obscuration (Lilley, 1955) [10].

3. INTERPRETATION OF OBSERVATIONS

When the radial velocities of the peaks of the profiles are plotted against longitude it is found that for the latitude strip at $b = -19°$ the variation is almost sinusoidal with a maximum at $l = 167°.5$ of +9·2 km./sec. and a minimum at $l = 179°.5$ of +2·8 km./sec. There is also an indication of such a behaviour at $b = -16°$. The average radial velocity of all the profiles for the Orion region is +6·6 km./sec. Hence the semi-amplitude of the radial velocity variation is about 3 km./sec. It is also interesting to find that the points $l = 179°.5$, $b = -19°$ and $l = 167°.5$, $b = -19°$ coincide with the edges of the H II ring. More observations are under way to determine the plane of maximum variation of radial velocity. The present observations can be successfully interpreted if we assume that the whole gaseous mass contained inside the H II ring is in rotation about an axis perpendicular to the plane of the Galaxy, passing through the point $l = 173°.5$, $b = -19°$ and with a linear velocity of rotation of about 3 km./sec. Preliminary calculations indicate that the observed ellipticity of the H II ring is consistent with the hypothesis of rotation of the whole gaseous mass. Detailed calculations are in progress to check on the consistency of having a gaseous cloud of the estimated mass, size and shape rotate at the above rate and the study is being extended to include possible magnetic effects from the galactic field.

On the basis of Strömgren's theory we can estimate the dimensions of the H II regions associated with the various groups of stars at the densities estimated above. Let us first take the giant H II ring. The obvious symmetry of the ring precludes the possibility of its excitation being due to any arbitrary distribution of exciting stars. The only small homogeneous group of stars is the Trapezium cluster and considering the nine stars which are close together all of spectral type O9·5 or B0, the observed diameter of 120 parsecs for the ring requires only a density of about 1·6 atom./cm.^{3} This is certainly too low a density to be reconciled with the 21-cm. observations. For a density of 5 atom./cm.^{3} the diameter of the H II region comes out to be about 56 parsecs. Moreover, if the Trapezium Cluster were the source of excitation, then practically all the hydrogen inside such a region should be ionized. This certainly is not the case since we observe no marked decrease in H I intensity at the centre of the region. The only valid conclusion appears to be that the density near the OB stars is so high that practically no radiation escapes outside these dense regions, to be available for ionization. Greenstein's (1946) [12] investigation of the Orion nebula, the appearance of the Horse Head nebula, as well as the estimate made earlier for the region near σ Orionis, tend to support the conclusion of very high density in these few regions (Seaton, 1953) [13]. If this is true, then we have to look for a different mechanism for the excitation of the giant H II ring.

Returning to the 21-cm. observations, let us consider a spherical, expanding region. The line profile for the centre of such a region should contain two peaks separated by the maximum positive and negative velocities of expansion. Since the density distribution is not necessarily uniform in all directions, the velocity of expansion will also not be the same in all directions. From aerodynamic considerations (see Oort (1946) [14]; Burgers (1946) [15]), it follows that the velocity will be greatest in regions of low density and smallest in regions of high density. As we move away in the sky from the centre of the region, the separation of the peaks should become smaller and the two peaks should coalesce when the separation is smaller than the half-width due to random motions alone. Let us assume a random velocity of 6 km./sec. We predict then for an expanding region with a diameter of 90 parsecs and at a distance of 500 parsecs that we may expect single peaks farther than 6° from the centre of the expanding region. The distance could be considerably less than 6° if the velocity were not uniform in all directions. Present observations indicate that the centre of this expansion is approximately at $l = 173\overset{\circ}{.}5$, $b = -18\overset{\circ}{.}5$. Further observations are being undertaken to locate the centre more accurately. The fact that we do not observe double-peaked profiles at distances more than about 3° from this centre indicates that either the diameter of the expanding region is smaller or the velocity is not uniform in all directions. We shall take as an approximation a diameter of 85 parsecs. We can estimate the maximum distance of the centre of expansion from the observation of the interstellar components in the spectrum of η Orionis. This star is one of the nearest in the association and is estimated to be at a distance of 360 parsecs. Hence it seems likely that the centre of expansion is on the inner edge of the spiral arm, in which case the higher density in the spiral arm might slow down the velocity of recession. If we take the maximum observed velocity as 12 km./sec. and a radius of 42·5 parsecs we get a value of 3·3 million years for the interval since the expansion began.

The following table gives approximate positions of some centres of interest:

Object	l	b
Orion nebula	176°.5	−18°
Horse Head nebula	174°.5	−15°
Centre of H II ring	173°.5 ± 2°	−18° ± 2°
Centre of OB association	172° ± 2°	−21° ± 1°
Centre of 21-cm. expansion	173°.5 ± 1°	−18°.5 ± 1°

We note from the above tabulation that the three latter centres are probably the same, whereas the Orion nebula is not directly connected with the centre of expansion. In this connexion it is interesting to recall the discovery by Blaauw and Morgan (1954) [16] that the motion of AE Aurigae and μ Columbae indicates that the two stars may have had a common origin in Orion. They found that these two stars move with the same speeds—127 km./sec.—in opposite directions away from the Orion region. They give the point of origin of the two stars as $l = 174°.8$, $b = -17°.7$, but the uncertainties in the observational data are such that the point of origin might well be moved down to $l = 173°.5$, $b = -18°.5$. They estimate that the stars must have left their point of origin about $2{\cdot}6 \times 10^6$ years ago. This estimate is in good agreement with that made above from the radio observations. Though Blaauw and Morgan were inclined to believe that the point of origin might be close to the Orion nebula, it is more logical to attribute the motion of the two stars and the expansion of the gases to one and the same cause and hence expect the two centres to coincide.

We seem to have the following picture: there exists a region of expansion of neutral hydrogen associated with a grouping of early-type stars, all of these features being bounded by a giant H II ring. The observed intensity of 21 cm. radiation is incompatible with the idea that the whole region is one of high ionization. But there are many small regions of high ionization around the early-type stars. However, the giant H II ring cannot be the edge of a Strömgren sphere since in such a case the interior of the sphere also must be completely ionized. Hence the giant H II ring may be part of a thin shell, which is excited by an unknown mechanism, but with direct stellar radiation playing only a subsidiary role.

Two different mechanisms have been put forward to explain the origin of stellar associations and their associated expansions. The first mechanism was proposed by Öpik (1953) [17]. According to Öpik's theory the giant H II ring is the remnant of the expanding shell of a supernova. The initial large velocities of a supernova explosion are resisted by the inertia of the surrounding interstellar gas and the expansion is decelerated in proportion to the mass of interstellar gas displaced from the volume occupied by the shell. His estimates indicate that the observed radius should correspond to a present velocity of expansion of 10 km./sec. and an interval of about $1{\cdot}5 \times 10^6$ years since the supernova explosion. These estimates are very approximate. During the process of expansion the compressed shell is supposed to have condensed into stars. The stars by this mechanism would have the velocity of expansion of the shell at the time of their formation. The different velocities of expansion of the stars in our case could presumably be due to their birth at different epochs of the expanding shell. One consequence of this mechanism is that the ages of the stars and the interval since the supernova outburst need not be precisely the same.

In this connexion it is interesting to recall a recent suggestion by Ambartsumian (1955) [18] that the origin of stellar associations is probably a single body—a proto-star. This proto-star is supposed to divide and form a trapezium system which in turn gives rise to an association.

In the second mechanism, proposed by Spitzer and Oort (1954, 1955) [6, 7], the initial expansion is set off by the formation of a hot star in the middle of dense clouds of dust and gas. The resultant differences in pressure in the H II and H I regions give rise to various aerodynamical phenomena, for example the production of shock waves at the boundary of the H I and H II regions, and provide energy for the acceleration of H I clouds. It is supposed that the resultant conditions are sufficient for the formation of expanding groups of stars. However, Spitzer and Oort (1955) [7] point out that this mechanism cannot be responsible for the acceleration of the two stars AE Aurigae and μ Columbae already discussed.

Again, according to this theory, 21-cm. profiles should show for the Orion region maximum hydrogen with negative radial velocity in the direction of the early-type stars. But, as pointed out earlier, observations indicate that this maximum occurs in a region devoid of early-type stars. Also the presence of the early-type stars within giant symmetrical H II ring is not to be expected from the Spitzer–Oort theory, since in their theory the stars are supposed to be formed at the boundary of H II regions. However, the observations of interstellar absorption lines indicate that the Spitzer–Oort mechanism may provide the acceleration for the small clouds responsible for their appearance. But it seems unlikely that a similar mechanism is responsible for the whole range of expansion phenomena of neutral hydrogen observed at 21 cm.

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