INVITED DISCOURSE C

given to participants in the General Assembly at 14^{h} 00^{m} on Monday 31 August 1964 in the Auditorium Maximum of the University in Hamburg by

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on

STRUCTURE AND EVOLUTION OF THE GALACTIC SYSTEM

I. *General composition. Different populations*

The Galaxy in which we live is composed of three ingredients: stars, interstellar gas and cosmic rays.

The bulk of the mass is in the stars. A fair estimate can now be made of the amount of gas. It is probably between 5 and 10% of the total mass of the system.

The cosmic ray particles have a negligible mass density, but a considerable energy density, comparable to the kinetic energy of the interstellar gas. Their velocities are so high that they would leave the system in a time of the order of 100 000 years if they were not constrained by magnetic fields. The current theory is that cosmic rays, except for some rare particles with exceptionally high energies, are kept in the Galactic System by magnetic fields. As the latter are frozen in the interstellar gas, the cosmic rays exert a pressure on this gas and may thus influence its motion and distribution.

It is not at all clear what role the galactic magnetic fields play in the dynamics of the interstellar gas. At the moment we seem to know more about what they *cannot* explain than about their *positive* contribution to the understanding of the complicated phenomena observed in the gas. But the determination of structure and strength of these fields is of fundamental importance. In combination with the cosmic rays they determine the radiation at radio frequencies. Anything we can learn about the magnetic field in the Galaxy may help to obtain an insight into the mechanism of radio sources in general. We are now just at the point where first glimpses of the structure of the galactic field are emerging. I shall return to this in a later part of the lecture.

The stars and the gas of which our Galaxy is composed make a rather complicated picture. On one hand we observe objects with very little concentration to the galactic plane and for which the axial ratio of the surfaces of equal density is between 0·5 and 1. Globular clusters and RR Lyrae variables with lowest metal contents, as well as the extreme subdwarfs, belong to this class, which is called halo population II.

At the other extreme we find the interstellar clouds and the stars recently formed from these clouds, such as O- and B-type stars and supergiants. These have been called extreme population I. They form a thin layer around the galactic plane; the thickness of the layer is about one hundredth of its extent in the plane.

The motions of the objects belonging to these extreme classes differ in a way corresponding to their difference in distribution. While the objects belonging to population I move in almost circular orbits making small angles with the galactic plane, the halo population II stars have large velocity components perpendicular to this plane, so that their orbits are in general strongly inclined. Their velocity components in the direction of the centre are *very* large, and the orbits therefore deviate widely from circles.

There are also classes of objects which are intermediate between the two extremes.

II. *Origin and evolution*

The cause of this dualistic, or rather composite, structure of the Galactic System must lie in the manner in which it was formed from the general intergalactic medium. In order to understand these fundamental characteristics of the System we must therefore consider its origin and evolution.

Galaxies must have formed from inhomogeneities in the expanding universe. Even the most superficial glance at the distribution of galaxies shows that the density distribution in the universe is extremely uneven. The largest-scale unevenness is that of the large clusters and irregular groupings of galaxies, like the Virgo cluster and its surrounding irregular annexes. Within these large groups there must have been density fluctuations on a smaller scale from which the individual galaxies were born. In both cases the density must have considerably exceeded the critical density of the expanding universe. This means that these regions could only expand to a certain maximum radius, and then collapsed under their own gravitation. The masses of gas which thus contracted into galaxies must have had irregular shapes.

Most galaxies rotate. We conclude from this that large gas currents existed in the universe. The size of these currents must have been of the same order as the dimensions of the proto-galaxies, so that they became endowed with an appreciable net angular momentum. This determined the axis of symmetry of the galaxy as it finally evolved.

Stars formed in the earliest stages must originally have been distributed in the same irregular fashion as the primeval mass of gas which detached itself from the surrounding universe. By the attraction of this mass they will subsequently have been concentrated towards its centre, and will have obtained high velocities in mainly radial direction. It is likely that in the course of time their distribution was randomnized by mixing, and by the presumably large initial irregularities in the gravitational field. They thus came to form a system which was symmetrical around an axis. However, there would seem to be no way in which the mixing process could lead to a considerable flattening: in respect to flattening, the system of the primeval stars must have conserved roughly the same shape as the original mass of gas from which it started.

The characteristics described are precisely those observed in the halo population II. We are thus led to identify this population with the stars formed in the earliest part of the history of the Galaxy.

That part of the gas which was not condensed into stars in these early phases evolved in a different manner. While contracting under its own gravitation it gradually transformed its original potential and kinetic energy into heat and radiation. The contraction may finally have resulted in a thin disk, with strong concentration towards the centre (Figure 1).

Stars must have formed during the contracting stage as well as after its completion. The former will have formed "systems" of intermediate flattening. The stars born after the gas had completely contracted should all lie close to the galactic plane. The process of star formation must have been fastest right after the collapse into a disk, when the gas was densest; it must have been particularly fast in the central region. The oldest disk stars, born at this epoch, must therefore be strongly concentrated to the centre. The process of star formation must have gradually slowed down, though it is continuing up to the present time.

I wish to stress that, although the sketch of the evolution of our Galaxy which I have described appears plausible, its plausibility should not mislead us into *believing* it. For there are other facts which show that very *im*plausible things occur in galaxies, in particular in their *nuclei.* It might be, for instance, that these nuclei had existed from the beginning and that, as Ambartsumian has advocated, they play a much more fundamental rôle in the evolution than being just the centres to which the collapsing material was concentrated.

However, I shall continue for the present to use the picture I have developed above.

Objects formed during the different stages of the evolution of the Galactic System can be distinguished by specific intrinsic properties, not only because the properties of a star change with its age, but also—and in fact principally—because the composition of the interstellar

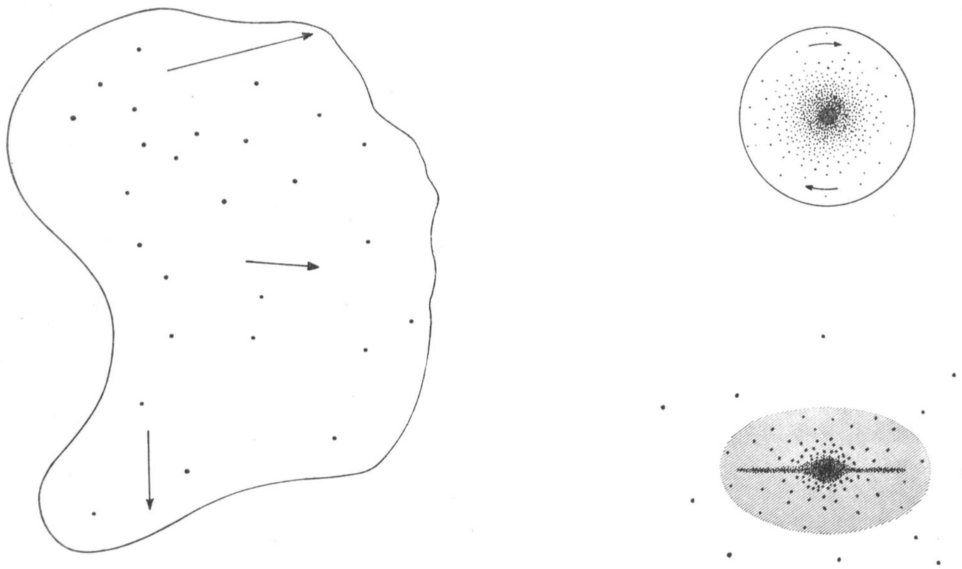

Fig. 1. *Schematic picture of the evolution of the Galactic System.* The picture on the left is the "proto-galaxy" at the epoch when it became an independent unit; the arrows indicate systematic velocities in different parts of the primeval mass of gas; the dots indicate stars or clusters formed before the beginning of the contraction. The pictures on the right show projections on the galactic plane and on a plane perpendicular to it, of the final state, after the contraction was completed. The thin horizontal bar in the lower picture represents the gas and the disk population (the outer limit of the disk is indicated by a circle in the upper picture), while the dots show the final distribution of the primeval stars of the left-hand picture (the so-called halo population II).

matter has changed systematically with time. Observations show that part of the objects formed during the halo phase of the system have metal abundances which are up to several hundred times lower than stars formed today. But there is also a considerable fraction of the halo clusters which shows only moderate metal deficiency. Among the disk clusters there seem to be none that are very metal poor, not even among the oldest. In the latter the metals are about five times less abundant than in the present interstellar medium. These facts indicate that the building of elements from hydrogen must have started soon after the birth of the Galaxy (or perhaps even before); in any case well before the initial gas had appreciably contracted. As no helium abundances are known for these old stars, we do not know whether helium already existed in the primeval medium, or whether this was also built up in the stars.

The building of elements has presumably taken place in the cores of heavy stars, the material being returned to the interstellar medium by explosions of these stars. The interstellar gas was thus gradually enriched with heavier elements. It is mainly by these differences in composition that individual stars and clusters can be assigned to different age groups, and that it may eventually be possible to obtain a complete picture of the evolution of the Galactic System.

As yet very little is known about the middle ages of our Galaxy. I shall therefore confine my discussion almost entirely to the earliest and the latest period of its history.

THE STELLAR COMPONENTS OF THE GALAXY

III. *The oldest stars and the contraction which must have taken place since the birth of the Galaxy*

Important new data have quite recently become available on space velocities of stars belonging to the oldest constituents of the Galaxy, viz. variables of the RR Lyrae type and subdwarfs of very low metal content. They indicate that in the vicinity of the Sun the velocity of rotation for these archaic stars is only about 50 km s^{-1}. This is five times smaller than the velocity of rotation of the interstellar gas and the known disk stars.

During the contraction of the swarm of stars formed in the "proto-galaxy" stage the halo stars will have gained kinetic energy by the contraction. They will also have gained some kinetic energy by encounters with local mass concentrations in the protogalaxy. However, from the fact that the bulk of their present energy is in the radial components of their velocities we can infer that the latter gain has been small compared to the kinetic energy derived from the contraction. Under these circumstances it must be possible, from the present density and velocity distribution of the oldest stars, to obtain a rough estimate of the original radius of the mass of gas from which the Galaxy was born. It will be somewhat of a lower-limit estimate, because the gas is likely to have lost some kinetic energy by collisions before all the halo stars were formed.

If we assume also—as was done in a recent article on this subject by Eggen, Lynden-Bell and Sandage—that the halo population did not gain or lose a considerable fraction of its present angular momentum during the evolution of the System, we can infer from the observed average momentum per unit mass in the halo population II the net angular momentum of the initial mass of gas. This teaches us something about the nature of the large-scale streamings which existed in the universe.

If no large fraction of the halo angular momentum has been lost during the contraction of the gas into a disk, the disk must also have about the same average angular momentum per unit mass as the halo stars. Since the halo rotates about five times slower than the disk, we are led to conclude that the mean radius corresponding to the mass distribution in the disk should be some five times smaller than the mean radius of the halo, and at least ten times smaller than the radius of the proto-galaxy; which gives an approximate idea of the initial dimension of the mass of gas which detached itself from the expanding universe to form the Galactic System.

IV. *Length of the halo- and intermediate-phase*

It is of interest to inquire into the approximate length of the period during which the stars of the halo and the intermediate populations II were formed. This must be of the same order as the time of collapse of the primeval mass of gas. If this collapse had not been hampered by collisions between irregular streams, it would have taken about 200 million years. The actual time will have been somewhat longer, but probably not very much. The stars of the halo population II must all have been formed in a time of this order; the populations with intermediate flattening have presumably been born in the same period. It may be that in the course of the contraction the gas became so hot that it could not radiate away its thermal energy fast enough to keep pace with the collapse. But it is unlikely that many stars would be formed in such a stage of high temperature. Star formation would in this case presumably recommence only after the gas had cooled down and condensed into a disk.

There are indications that during the ancient phase when the halo stars were born, star formation went on at a faster rate than during the disk phase of the Galaxy, and also that, apparently, conditions in this contracting stage were more favourable for the formation of large objects such as the giant globular clusters. Though the disk stage has lasted at least 50 times longer, no clusters of similar richness have been found in the disk except near the nucleus.

One might imagine that it was the slower rotation of the primeval gas and the large compression effects due to encounters between currents that favoured the birth of large stars and clusters.

That the period of collapse must have been particularly active in the formation as well as in the disintegration of stars is also indicated by the fact that in this stage which lasted perhaps 2% of the age of the Galaxy, about 20% of the elements heavier than hydrogen and helium have been formed.

V. *Mass of the halo*

Concerning the composition of the halo all we can say is that it *may* be similar to that of globular clusters. A minimum value for the total mass of the halo can be found from the density of late K and M subdwarfs which were found in our neighbourhood.

Some 5% of the total mass of the Galaxy may be estimated to consist of these halo dwarfs. There is no way for estimating how much more mass there may be in the form of intrinsically still fainter stars. The real mass of the halo therefore remains entirely unknown. It is quite possible that there might be enough halo stars to make the halo an important contributor, or even *the* most important contributor to the mass of the Galactic System. The uncertainty concerning the relative contributions of the halo and the disk to the total mass is the greatest obstacle in the way of constructing a model of the mass distribution in the Galaxy.

VI. *Mass density near the Sun*

In this connection I want to refer briefly to the possibility of determining the mass density in the general vicinity of the Sun by dynamical considerations. By comparing the way in which the density of a given type of stars decreases with increasing distance from the galactic plane with the velocity distribution in the same direction results have been obtained for the total mass density near the galactic plane. Of this total density about 20% can be ascribed to interstellar gas, and 40% to stars of known types including extrapolation to fainter dwarfs.

Roughly 40% remains unexplained. The possibility that the invisible mass is molecular hydrogen cannot be excluded; however, at the moment it appears somewhat more likely that it consists of intrinsically very faint stars. We do not know to what population they would belong, and this again introduces an element of considerable uncertainty for the construction of mass models of the Galaxy. It should be pointed out that the data on which the dynamical determination of the density is based are still extremely poor; an improvement of these data is highly desirable. This might well revise the conclusions about the invisible mass.

VII. *General mass distribution*

Important information concerning the general concentration of mass towards the centre is given by the rotational velocity of the gas, obtained from observations of the 21-cm line. These measures indicate that the average mass density within 500 pc from the galactic centre is roughly 50 times that near the Sun. It is interesting to note that both halo population II stars, such as RR Lyrae variables with periods longer than $0^d.4$, and old disk objects, like the planetary nebulae, show a much stronger concentration toward the centre. Baade has shown that at 1 kpc from the centre the density of the RR Lyrae variables is about 1000 times that near the Sun. For the planetaries it may be estimated that the density near the centre is also of the order

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of 1000 times that near the Sun. These data would seem to indicate that at most 10% of the mass density near the Sun can be attributed to population II stars.

In the period immediately following the condensation of the gas into the disk, at the time when the oldest disk stars were born, the gas must have been strongly concentrated to the centre. We can conclude this from the observed distribution of some types of disk stars like planetary nebulae, novae, population II cepheids, and long-period variables, which are all very much concentrated towards the galactic nucleus and show large density gradients near the Sun. At present the distribution of the gas is entirely different. This is evident from Figure 2, which shows the distribution of hydrogen atoms in our Galaxy and in the Andromeda nebula. We see that there is no trace left of a concentration to the centre. On the contrary: the density within about 5 kpc from the centre is decidedly lower than between 5 and 15 kpc. This is a very surprising result, indicating that in some way the gas may have been swept from this part into the outer regions. It is unlikely that the phenomenon has been caused by a changing fraction of molecular hydrogen, although this may be important in the nuclear disk within about 0·7 kpc from the centre.

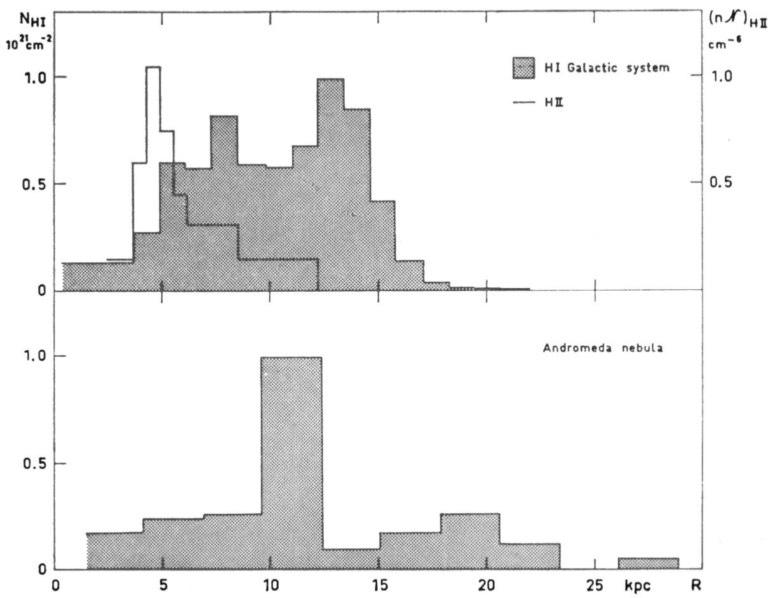


Fig. 2. *General distribution of hydrogen in the Galactic System and the Andromeda nebula.* The grey parts show the numbers of hydrogen atoms in columns of 1 cm ^{2} cross section perpendicular to the equatorial planes of the two systems. Abscissae are distances from the centre in kpc. In the upper picture the curve with the sharp maximum at $R=5$ gives the distribution of ionized hydrogen (after G. Westerhout and an unpublished investigation by H. van Woerden).

A phenomenon which makes the impression of being related to the relative emptiness of the central part of the gas disk is shown by the distribution of the sources of thermal radiation. This is likewise given in Figure 2. There is a strong concentration of ionized hydrogen near $R = 5$ kpc, just outside the region where the HI is deficient.

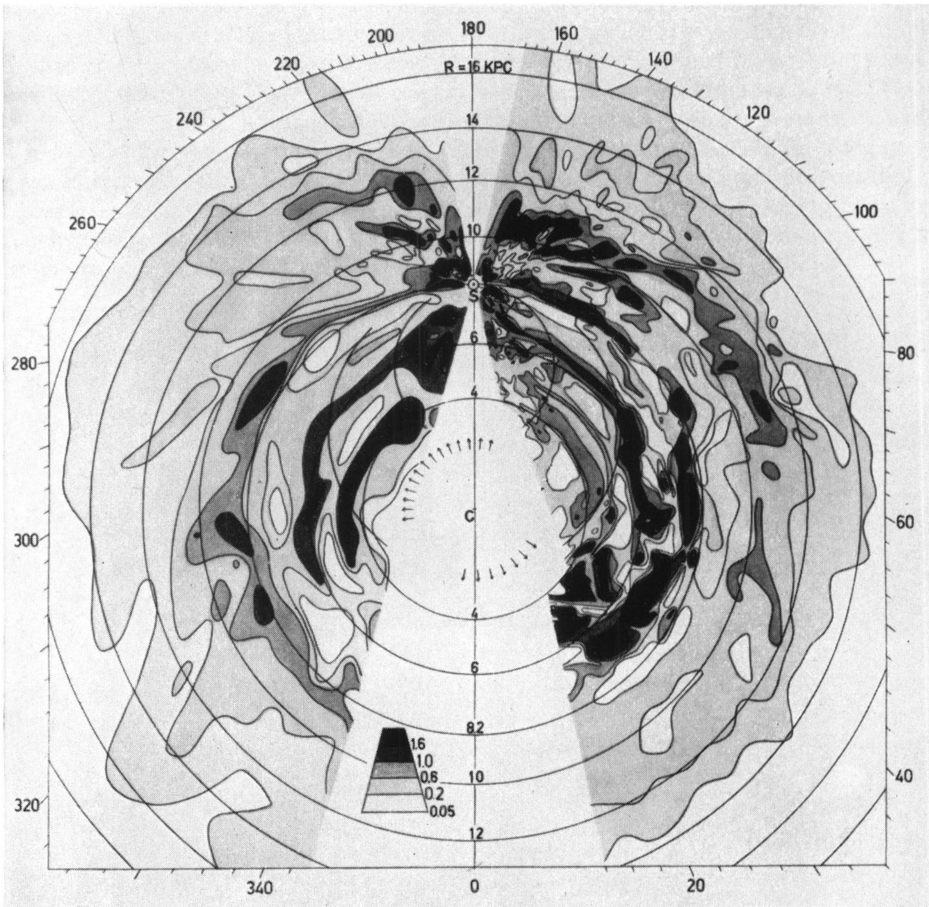


Fig. 3. *Spiral arms in our Galaxy*. The picture shows the distribution of hydrogen in the galactic plane as inferred from observations of the 21-cm line. The part between 13° and 252° longitude has been derived from observations in the Netherlands, while the part between 252° and 343° is based on Australian observations. In this picture the distance from the Sun to the centre is 8·2 kpc, while in other figures the recently adopted value of 10 kpc has been used.

THE INTERSTELLAR GAS

VIII. *Cloud Structure*

In the second half of my lecture I would like to focus your attention mainly on the gaseous component of the Galaxy and on objects which are intimately related with the interstellar gas.

Since 1951 the possibility to observe the hydrogen line at 21-cm wavelength has enormously extended our knowledge of the distribution and motion of the gas throughout the System. This advance was primarily due to the transparency of the galactic layer for radiation of this wavelength, so that the entire disk could be surveyed, while at optical wavelengths only a small part could be seen because of the strong extinction.

The gas is mostly concentrated in a very thin layer around the galactic plane. In this layer its distribution is very inhomogeneous: it is concentrated in clouds or sheets with a wide range of dimensions and forms; the best observed clouds have masses of the order of 100 solar masses and diameters of the order of 10pc; they have random motions averaging about 5 km s^{-1} in one co-ordinate. These irregular motions are kept up by the birth of bright stars of high temperature. These heat the gas locally, and set up interstellar winds. From time to time the gas is vehemently stirred up by interstellar hurricanes following the explosion of a supernova.

The clouds have a tendency to form large agglomerations with masses up to 10^5 solar masses.

IX. *Spiral structure*

If we consider the distribution of the gas on a still larger scale, such as has been done in the large 21-cm surveys made in the Netherlands and Australia, we see that the gas is arranged in long arm-like structures which must in all likelihood be identified with the spiral arms observed in spiral nebulae (cf. Figure 3).

The 21-cm measures not only inform us about the general distribution of the gas, they also give us the rotation curve of the Galactic System and the gravitational field in the galactic plane.

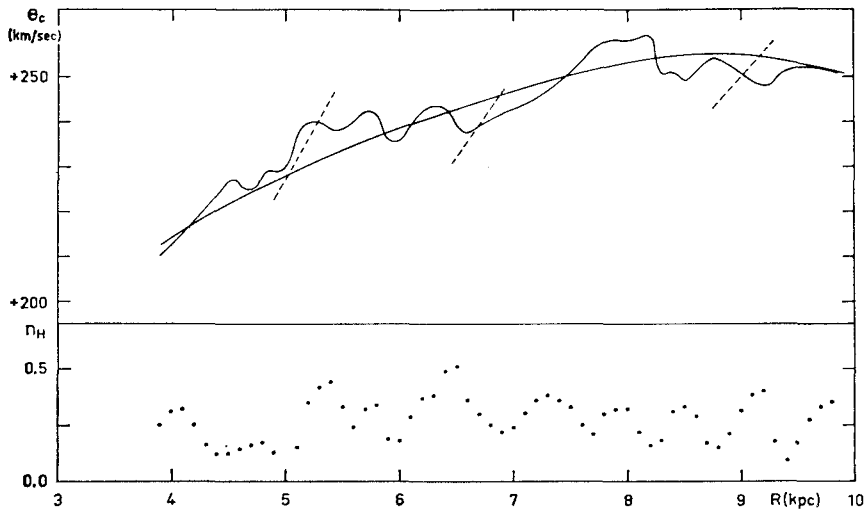
The rotation curve (Figure 4) is not smooth, but shows two major humps. The humps might be due to variations in the radial gravitational force caused by the concentration of mass in the spiral arms. If we interpret them in this way, they would give a means for estimating the total extra mass density in the arms. This is an information which is of essential importance for any theory of spiral structure.

We are still far from a convincing theory of spiral structure. Many theories have been proposed and some of these have greatly developed our insight in the problems involved. But, so far, it has not proved possible to work any of these out in a quantitative and entirely satisfactory manner.

We do not even know how the spiral structures are conserved against the disruptive action of differential rotation. This is a purely kinematical problem, which cannot be solved by axial asymmetry in the field of force. If in our own Galaxy or in M81 the matter in the spiral arms moved in circular orbits with a velocity that depends only on the distance from the centre, the spiral structure in either of these galaxies would be virtually dissolved in about 1·5 revolutions, or in 2 or 3% of the age of these galaxies. It is evident that this cannot happen, and that, therefore, either the motion of the gas in the arms must deviate systematically from such a circular motion, or that there are unobserved systematic motions of the gas *between* arms that compensate the dissolution.

It seems probable that in the development of spiral structure gravitational forces exerted by the arms themselves, or by a generally non-axisymmetric distribution of matter, play a very important rôle. But beside gravitation hydrodynamical and possibly also magneto-hydro-dynamical effects must form an essential factor.

Apart from theoretical arguments this essential rôle of the gas can be empirically deduced from two interesting observations. Many years ago Baade drew attention to the fact that dense



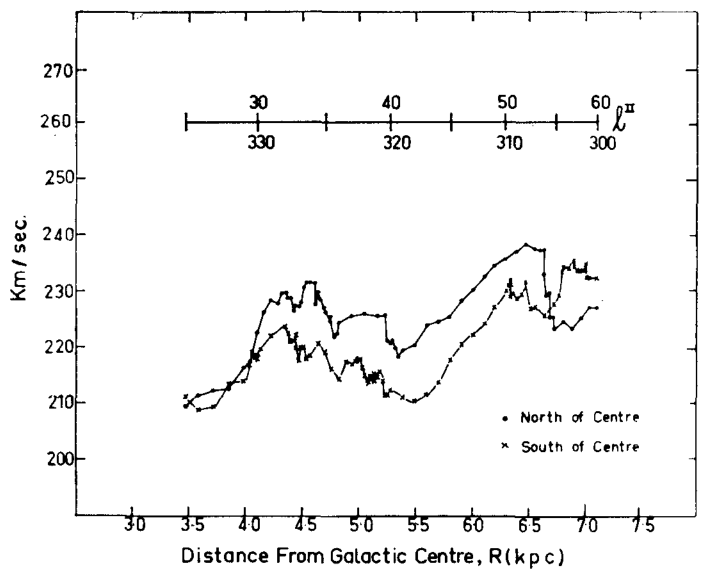


Fig. 4. *Rotation curve.* The upper part shows the velocity of rotation as a function of distance from the centre derived from recent observations in Dwingeloo (W. W. Shane). The lower picture, due to F. J. Kerr (Parkes telescope), shows a comparison between the rotational velocities at different sides of the centre. The distance from the Sun to the centre is 10 kpc for the upper figure and 8·2 kpc in the lower one.

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clusters of galaxies seldom contain spirals, but that they do contain large numbers of So galaxies. The So galaxies are characterized by disks that are as thin as those of spirals; but they show no spiral structure. The earlier-type So galaxies contain very little dust, and are presumably almost devoid of gas. Spitzer and Baade have suggested that the high frequency of So nebulae in dense clusters is due to the circumstance that collisions should be sufficiently frequent in such clusters for every galaxy to have experienced at least one collision with another

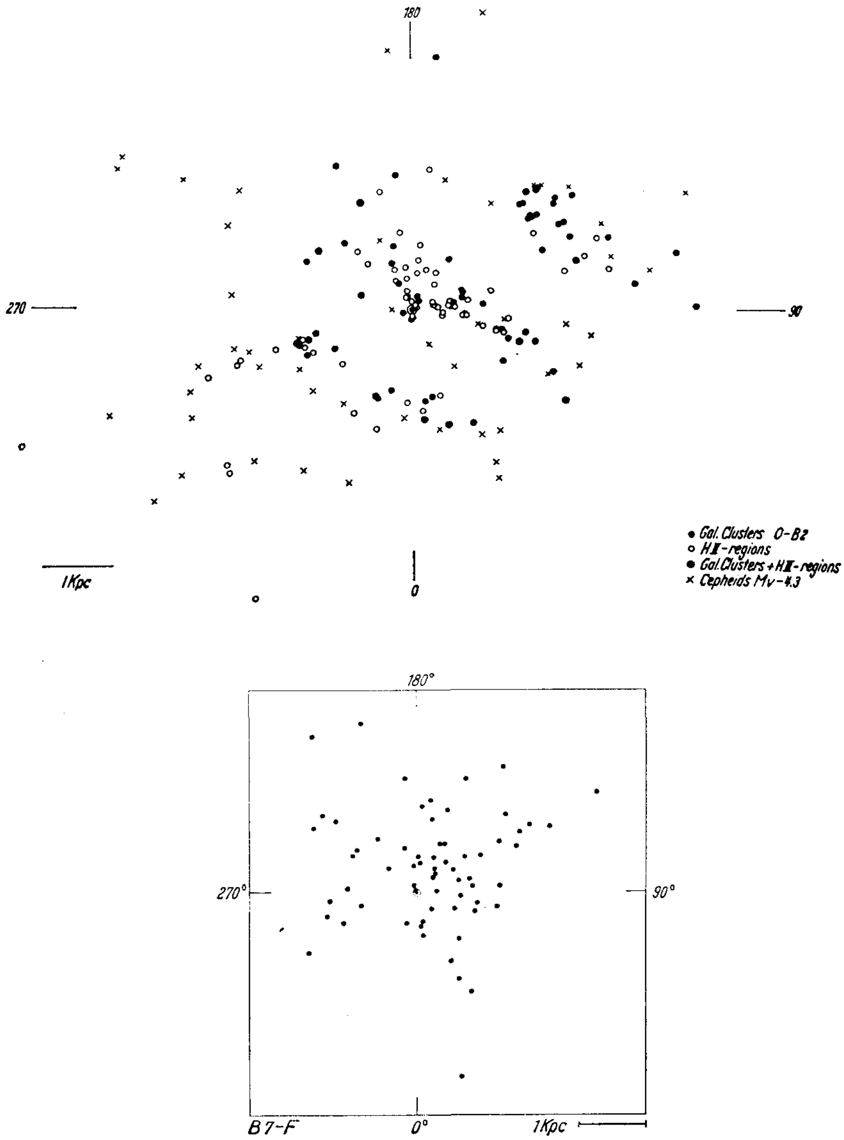

Fig. 5. *Distribution of clusters of different ages.* The upper part contains young clusters, H II regions and cepheids (ages less than approximately twenty million years); the clusters plotted in the lower half have an average age of about two hundred million years (after W. Becker, *Z. Astrophys.*, **57**, 117, 1963 and **58**, 202, 1964).

galaxy. In such a collision practically all the interstellar gas will be swept away from the colliding galaxies. With the loss of gas the galaxies apparently also lost their capacity to form spiral arms, though they did *not* loose their flat shapes.

The second argument indicating that spiral arms consist practically entirely of gas and not of stars comes from recent investigations of the distribution of galactic clusters, cepheid variables and Be stars of different ages. These show that only the objects which are younger than 20 or 30 million years are distinctly concentrated in the spiral arms. An illustration of this is given in Figure 5, taken from an investigation by W. Becker. It shows on one side the distribution of young clusters, with ages less than about 20 million years, and in the other half the distribution of clusters which are about 200 million years old. The latter show no sensible correlation with the arm structure displayed by the former group. Apparently, the clusters move away from the gas arms in which they were born. With individual velocities averaging about 10 km s^{-1} they move through 500 pc in 50 million years. As the half-width of the arms displayed by the youngest clusters is about 300 pc, it is not implausible that they would have moved far enough to efface their original relation to the arms. These facts seem to indicate that the spiral arms are made entirely of gas and also that it is not gravitation alone which keeps the arms together, but in addition something that is peculiar to the *gas*. The gas density in the arms might be rather higher than the density of atomic hydrogen found from the 21-cm observations. If the waves in the rotation curve which I have mentioned before are ascribed to gravitational attraction by the arms, they would indicate a total density that is about four times higher than the HI density.

In addition to gravitation and gas-dynamical effects on spiral arms we must also consider the possible influence of magnetic fields. At present it is still an open question whether or not they are significant for the dynamics of spiral arms.

Because no fully satisfactory picture of the spiral problem can yet be given, and the problem is a very difficult one, I will not discuss it any further this afternoon.

X. *Bending of the outer edges*

I now wish to direct your attention to the remarkable phenomena which the 21-cm observations have revealed in the outermost and in the innermost parts of the disk.

In the outer parts the disk, which is remarkably flat over the whole region within 8 kpc from the centre, bends strikingly upward on one side, and downward on the opposite side of the centre; the deviations from the mean galactic plane run up to about 0·5 kpc at distances of 15 kpc from the centre. The explanation of this curious bending is still uncertain.

XI. *Expanding arms in the central region*

Quite unexpected things are encountered in the central region of the disk. A striking feature is an arm-like structure which passes between us and the galactic centre, as is evident from the fact that it is seen in absorption against the strong radiosource at the centre (Sagittarius A). At this point it has a radial motion, away from the centre, of 53 km s^{-1}. The arm is usually referred to as the 3-kpc arm, because of its estimated distance from the centre. It is a quite normal and fairly regular spiral arm. The mass of gas contained in it is of the same order as the mass in a similar length of one of the outer arms, and is about half of the total mass of hydrogen in the central part. The structure and the motions of the 3-kpc arm have been extensively studied by Rougoor at Leiden. He has likewise studied the motions in other parts of the central region. There is a second "expanding" arm on the far side of the centre. At the longitude of the centre this has a radial motion, again away from the centre, of 135 km s^{-1}. Both "arms" have also transverse velocity components in the direction of the rotation of the Galactic System, but there are strong indications that at the point where the arm which passes behind the centre is

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observed tangentially, at a distance of probably about 1 kpc from the centre, its rotational velocity is very much smaller than the circular velocity corresponding to the galactic gravitational field. While the latter is about 250 km s^{-1}, the transverse velocity of the arm is probably not much larger than 50 km s^{-1} at this point.

The total amount of gas which these expanding arms carry away from the central region is at present of the order of a solar mass per year. The radial motions would empty the whole disk of 3 kpc radius in a time of the order of 30 million years. The cause of these large radial motions is still unknown. We also do not know whether the outward stream is a continuous phenomenon, or whether it happens only occasionally. I shall return to these matters in a few moments.

XII. *The nuclear disk*

Inside these expanding arms we meet with again totally different things. Within 800 pc from the centre the gas appears to be in rapid rotation around the centre and to form what I shall refer to as a "nuclear disk" (Figure 6). The angular velocity in the very thin disk increases

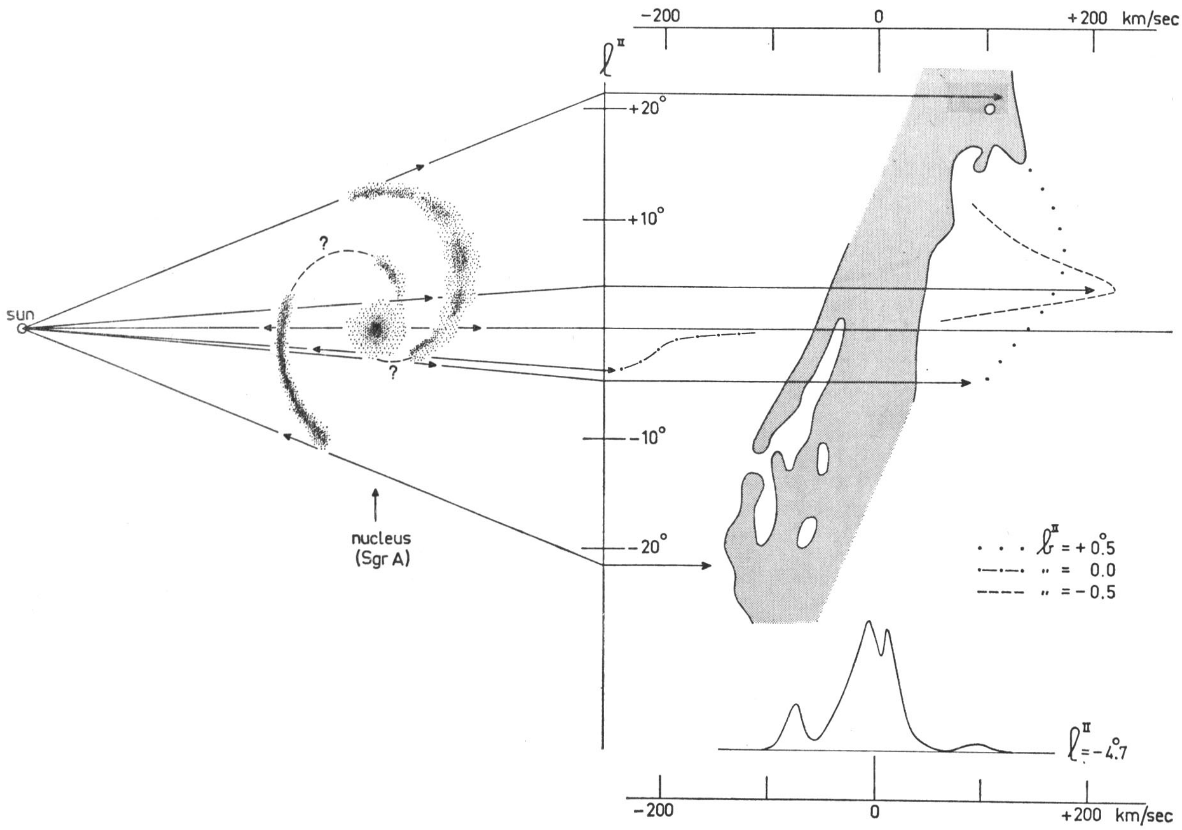

Fig. 6. *Sketch of possible arrangement of the gas in the central part of the Galaxy*. The arrows in the left-hand part indicate the observed radial velocities, the actual sizes of these velocities being shown in the right-hand part (after G. W. Rougoor, *Bull. astr. Inst. Netherlds.* **17**, 381, 1964).

steeply towards its centre. It is not unlikely that in this disk there is an approximate balance between centrifugal force and gravitation. The gravitational force required is just about what

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one would expect if the mass in our Galaxy were as strongly concentrated toward the centre as it is in the Andromeda nebula. The mass concentration must be almost entirely due to population II *stars*; the gas itself can make only a small contribution.

The total amount of atomic hydrogen in the nuclear disk equals about five million solar masses. A striking characteristic is the very sudden and sharp outer edge, as shown in particular by the hydrogen-line profiles near $l^{\mathrm{II}} = -4\overset{\circ}{.}5$, at 800 pc from the centre. Outside this edge the rotation of the gas seems to drop steeply to a very low value.

Although the principal motion in the disk is its rotation, there is also evidence of fairly large radial motions in restricted regions. These are visible in a particularly striking manner in the strong absorption lines of OH which have recently been discovered in Australia. But before directing your attention to these remarkable observations I must say something about the information which can be derived from the radio *continuum.*

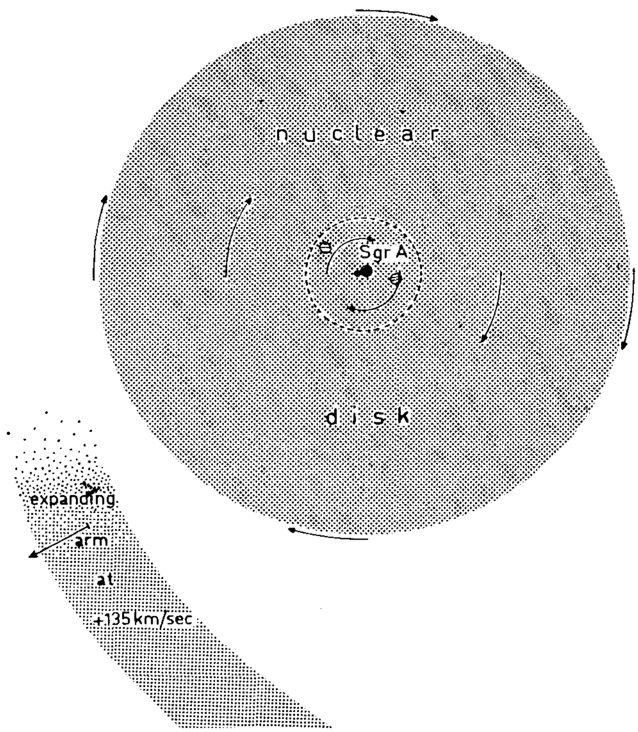

Fig. 7. *Nuclear disk and Sagittarius radio source.* The rapidly rotating disk has a rather abrupt outer boundary at 800 pc from the centre. In reality, the distribution in the disk is irregular, and some parts show considerable radial motions. The dashed circle, with a radius of 150 pc, shows the half-intensity contour of the *broad* component of Sagittarius A, four *concentrated* components of which are indicated by small circles.

Observations of the general radiation have shown that there is a very strong radio source, the "Sagittarius source", whose centre coincides with the centre of the disk. Its complex structure has been studied by many astronomers, in particular by Drake in Green Bank, Pariiskii at

Pulkovo and Lequeux at Nançay with high resolving power. The two strongest components, which are presumably right at the galactic centre, are separated by about 25 pc, and have diameters of 10 and 40 pc, respectively. There are two other, fainter, components on either side of the centre, at a distance of about 100 pc (Figure 7). All these components are embedded in a general region of enhanced radiation, which has a halfwidth of about 300 pc in the galactic plane. There is still some uncertainty about the nature of these sources. The available radio-spectrum data indicate that the strongest and most central concentration emits synchrotron radiation, while the two components about 100 pc from the centre are HII regions. The radiation coming from the wider distribution must be, at least partly, synchrotron radiation. The central components are intrinsically about 500 times brighter than the Orion nebula. This is by no means abnormally bright for the nucleus of a galaxy.

All attempts to find the Sagittarius source by optical means have failed. This may be due to the very strong absorption in the galactic disk in this direction, but it might also indicate that our supposition that the radiation is partly thermal was wrong. The only traces of matter that have been found optically in the central region, by Courtès, at the Observatoire de Haute-Provence, are faint wisps of H_α and [NII] omission. Judging from their velocities these seem to pertain to the nuclear disk.

With the large Australian radiotelescope at Parkes Robinson, Gardner, van Damme and Bolton have during recent months discovered in the nuclear disk absorption of OH of quite unprecedented strength. Comparison with HI absorption and emission in the same region indicates that the ratio of the number of OH molecules to that of hydrogen atoms must be more than 1000 times higher than in the general vicinity of the Sun. It looks as though almost all the oxygen in the small disk is bound in OH radicals.

Because the absorption coefficient of OH is much larger than that of HI it can be observed in absorption over the whole of the Sagittarius source, and even against a rather weak source near 3° longitude. The observations indicate that large concentrations of OH occur probably over the whole nuclear disk. Locally these concentrations show large deviations from circular motion. In some parts there appear to be radial motions of about 130 km s^{-1} directed away from the centre. Near the most concentrated component of Sagittarius A a considerable amount of gas seems to be flowing *inward*, towards this component, with velocities ranging from 0 to 80 km s^{-1}. The observations do not conflict with those of the 21-cm emission, but they show smaller-scale phenomena which were partly wiped out in the larger beam of the 21-cm emission observations. We must still conclude, from these latter observations, that for the bulk of the gas in the nuclear disk the principal motion is one of rotation.

Perhaps the most intriguing feature of these OH observations is that the intensity ratios of the four components of the OH band indicate that everywhere over the disk the optical depth for the strongest components is between about 4 and 10. As the apparent, overall optical depth is only about 0·5, this indicates that everywhere over the disk the OH must be concentrated in small clouds, each of which has a great optical depth, but which together cover only about half of the source of continuous radiation.

I am greatly indebted to Dr Bolton for allowing me to communicate in this lecture these results which are still mostly unpublished.

XIII. *Origin of the expanding arms*

There have, of course, been several speculations concerning the origin of the large radial motions observed in the central part of our Galaxy.

In order to provide a background for these speculations it is desirable to make some remarks on the nuclear regions of *other* galaxies. We note, in the first place, that in these regions the

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motion of the gas seems often to deviate widely from circular motion. Observations of emission lines near the nucleus have been made in the Andromeda nebula by Münch, while a very interesting investigation of the central region of M 51 has just been completed by Margaret and G. R. Burbidge; I am indebted to the latter authors for permission to quote from their still unpublished article. In the region within 30″, or 600 pc, of the centre they find superimposed on a general rotation expansion velocities up to about 150 km s^{-1}. These motions come in streams, probably connected with the intricate multi-armed spiral structure in this inner region, and they show great irregularities. In some directions the velocity field appears to be reversed, and matter is streaming inward to the centre. In the small bright nucleus of 30 pc radius high turbulent motions are observed, with a velocity dispersion of the order of 200 km s^{-1} in one co-ordinate. This phenomenon resembles on a small scale the gigantic internal motions found in the very bright nuclei of the so-called Seyfert galaxies. Münch's observations in the region within 500 pc of the centre of the Andromeda nebula are much less extensive. But they also show large deviations from circular motion. Apparently, nuclei of galaxies can sometimes supply huge quantities of large-scale kinetic energy to the gas. How they do this is still an enigma.

The idea that galactic nuclei may be the seat of unknown forms of energy, and even of an unknown state of matter, has already many years ago been put forward by our President Ambartsumian. He has on many occasions stressed the enigmatic character of nuclei of galaxies and their essential importance for phenomena observed in these galaxies (cf. Eleventh Solvay Conference, Brussels, 1958, p. 241, and Thirteenth Solvay Conference, Brussels, 1964, in press). An exhaustive survey of all related phenomena has recently been given by G. R. and E. M. Burbidge and Sandage in an article entitled "Evidence for the Occurrence of Violent Events in the Nuclei of Galaxies" (*Rev. Mod. Phys.*, **35**, 947, 1963).
There is now, indeed, a great deal of evidence—especially in connection with radio sources—showing that explosive events involving masses of the order of a million or more times the mass of the Sun occur from time to time in the nuclei of galaxies. With this evidence in mind it is tempting to suppose that the expanding motions of the arms in the central part of our Galaxy have been caused by such a gigantic explosion in the nucleus. This should then have occurred some ten million years ago, and should have involved a mass of the order of 10^7 solar masses, if the explosion would have been more or less isotropic. Part of this mass would have swept up the gas already present in the galactic disk, and would have built up the expanding and rotating arms. Such a supposition sounds fantastic, and would hardly be interesting if it were not for the direct evidence that violent explosions of such grandeur do occur. It would take me too long to show how convincing this evidence is. But there is one particular aspect which I want to stress, because it is immediately relevant to our problem. If we consider the 20 brightest galaxies in our nearest surroundings we find that in at least two of these something in the nature of such a superexplosion must have taken place during the last few million years. The one case is that of M 82, where the evidence for a recent explosion involving some million solar masses is direct and convincing (Lynds and Sandage, *Ap. J.* **137**, 1005, 1963); the other is NGC 5128, which is the radio source Centaurus A, which appears to be in the midst of a process of eruption. The inference to be drawn from this small sample is that violent nuclear events are things which are quite common, and that, therefore, it is not so far sought as it might first have appeared to invoke them also for explaining the expanding phenomena observed in our Galaxy and in M 51.

I want to stress that there is not the least *proof* that the expansion of the arms in our Galaxy has been caused by an explosive event. We can by no means exclude the possibility that magnetic fields, or a strongly asymmetrical gravitational field, are causing the gas to stream out with such high velocities.

Whatever explanation is chosen one is faced with the problem of how the gas which is now seen to be flowing out has previously come *into* the nuclear region. It is still impossible to answer this question. I have to leave it in its un-answered state, like so many of the other problems I have discussed.

If explosive events are invoked for explaining the expanding arms we should ask ourselves what other observable consequences would have to be expected, and also whether there are no observations which contradict the hypothesis.

There is, in the first place, the serious difficulty of how to account for the existence of the nuclear disk, which must either have been formed in an improbably short time, or it must in some way have been able to survive the explosion. Secondly we must consider what has happened to that part of the mass which was thrown out in directions making an appreciable angle with the galactic plane. In so far as the angles were not too large these parts of the shell may have swept up fairly massive agglomerations of gas. These should then be moving away from the centre at higher velocities than the expanding arms.

In Leiden W. W. Shane has made an extensive survey of the region just outside that of the expanding arms from observations with the Dwingeloo radio telescope; one of the purposes of this survey was to see if any traces of expansion could be found farther than 4 kpc from the centre. No such traces have been found in the plane, but two high-velocity features were discovered at somewhat higher latitudes. One of these has been studied in detail by Miss Smith. Figure 8 shows the density distribution. The cloud complex has a velocity of $+ 90$ km s^{-1},

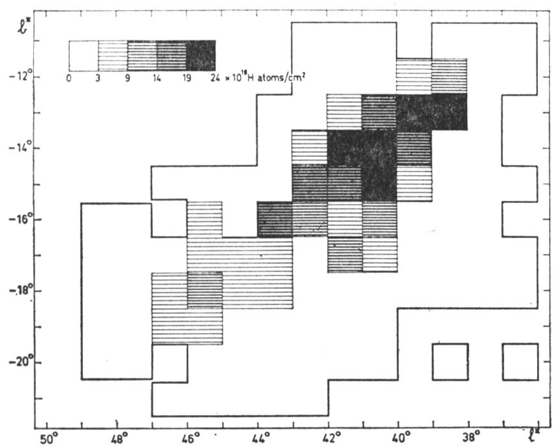

Fig. 8. *Density distribution in a cloud moving at a high velocity*. The shadings indicate different surface densities, in units of 10^{19} hydrogen atoms per cm^2 (after Gail P. Smith, *Bull. astr. Inst. Netherlds.*, **17**, 203, 1963). The region within the heavy line was completely surveyed.

which slightly exceeds the maximum differential rotation in this longitude. It extends over a surface of $8° \times 3°$, the centre being at $-15°$ latitude. It is well separated from the disk gas at the same velocity. The nature of the object is entirely unknown, as we have no observations from which its distance could be deduced. It might be a near-by object of unusual nature, or it might lie at a distance comparable to that of the tangential point, at 7·5 kpc, in which case the mass of hydrogen contained in it would be half a million solar masses. It is just possible that we witness here a feature coming from an explosion in the nucleus.

Gas expelled under still larger angles with the galactic plane may either have left the Galaxy altogether, or it may have moved out to large distances from the plane and ultimately fall back into the galactic layer at large distances from the centre. G. R. Burbidge and Hoyle have suggested that the gaseous halo of the Galactic System might have been formed in such a way, and that this halo might, therefore, be a transient phenomenon.

XIV. *The Galactic Corona*

This brings me to a consideration of the one important feature of the Galaxy that I have not yet discussed, namely the extended gaseous mass in which the Galactic System appears to be embedded.

We have seen that most of the interstellar gas is strongly concentrated toward the galactic plane. But, apparently, there is also *some* gas at large distances from the disk. The earliest and most convincing evidence of this presence comes from observations of the radio continuum. The galactic disk is surrounded by an almost spherical "atmosphere" which emits radio waves. I shall call this extended atmosphere the galactic "corona", in order to distinguish it from the halo of old stars. It extends to a considerable distance beyond the Sun and shows remarkably little concentration toward the centre, as will be seen from Figure 9, copied from

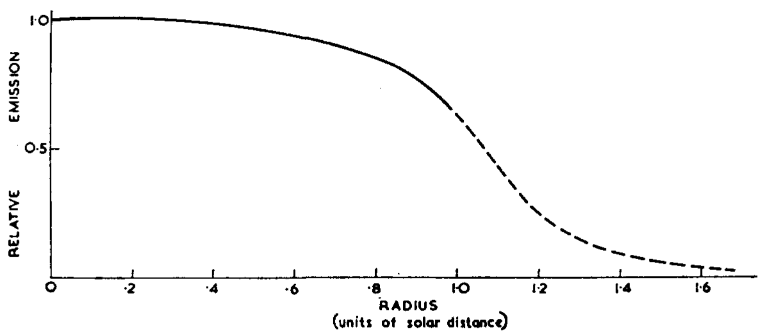

Fig. 9. *Emission from the galactic corona as a function of distance from the centre along the galactic plane* (after J. Pawsey).

an article by Pawsey. The radiation shows *some* concentration to the disk, but only in the inner parts; in the outer regions there is hardly any trace of a disk. The corona has a structure of its own. There are a few large features, like the well-known "Northern spur", which extends over at least a quarter of the sky, and many fluctuations of medium scale, with intensity variations by factors of the order of two (Figure 10). The radiation is strikingly polarized. At high frequencies almost complete linear polarization has even been indicated in some regions. The radiation must therefore be of the synchrotron type; it is produced by the interaction of cosmic ray electrons with the galactic magnetic fields. The structure observed in the corona should be a reflection of that of the magnetic field in the Galaxy. It may be expected, therefore, that very valuable information on the structure and the strength of the magnetic fields will ultimately result from observations of polarization and of Faraday rotation at different frequencies. Such observations are now successfully pursued in several observatories. They are becoming one of the most important lines of research into the structure of the Galactic System. Because of time limitations I refrain, however, from showing results. The observations are in a beginning stage, and we are still far from the goal of a comprehensible model of the magnetic field in the Galaxy.

The magnetic fields must be carried by interstellar gas. There must therefore be gas in the

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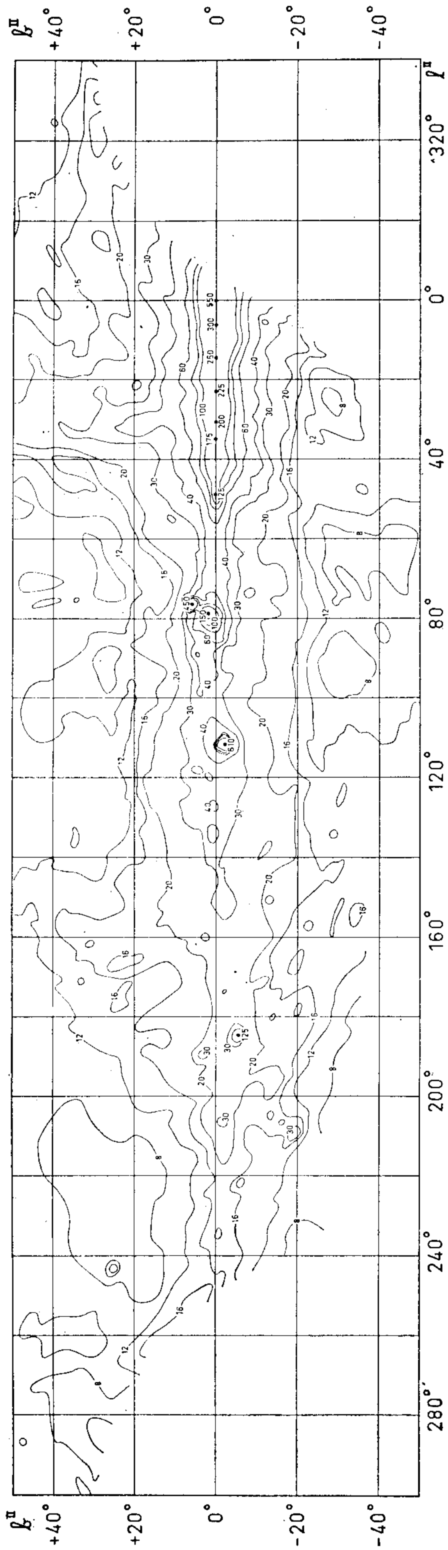

Fig. 10. *Distribution of continuous radiation at a wavelength of 73 cm.* Dots indicate discrete sources; the accompanying numbers are the maximum temperatures recorded on these sources (after Ch. L. Seeger, Gart Westerhout, R. G. Conway and T. Hoekema, *Bull. astr. Inst. Netherlds.*, **18**, 1, 1965).

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corona, and the structure of the gaseous corona should presumably bear some resemblance to that of the radio corona.

The first evidence for discrete gas clouds at considerable distance from the galactic plane was found by Münch and Zirin. They observed a number of distant early-type stars in high latitudes and found a few clouds with velocities exceeding 50 km s^{-1} and lying probably at distances of the order of 1 kpc from the galactic plane.

During the last few years a systematic search for HI clouds in moderate and high latitudes has been made by astronomers from Groningen and Leiden with the radio telescope in Dwingeloo.

In this survey a great number of features were found having high or relatively high velocities, and which are presumably situated at considerable distances from the galactic plane. The velocities show a remarkable distribution. They indicate that there are streams of gas of large extent flowing towards us from a direction around 120° longitude.

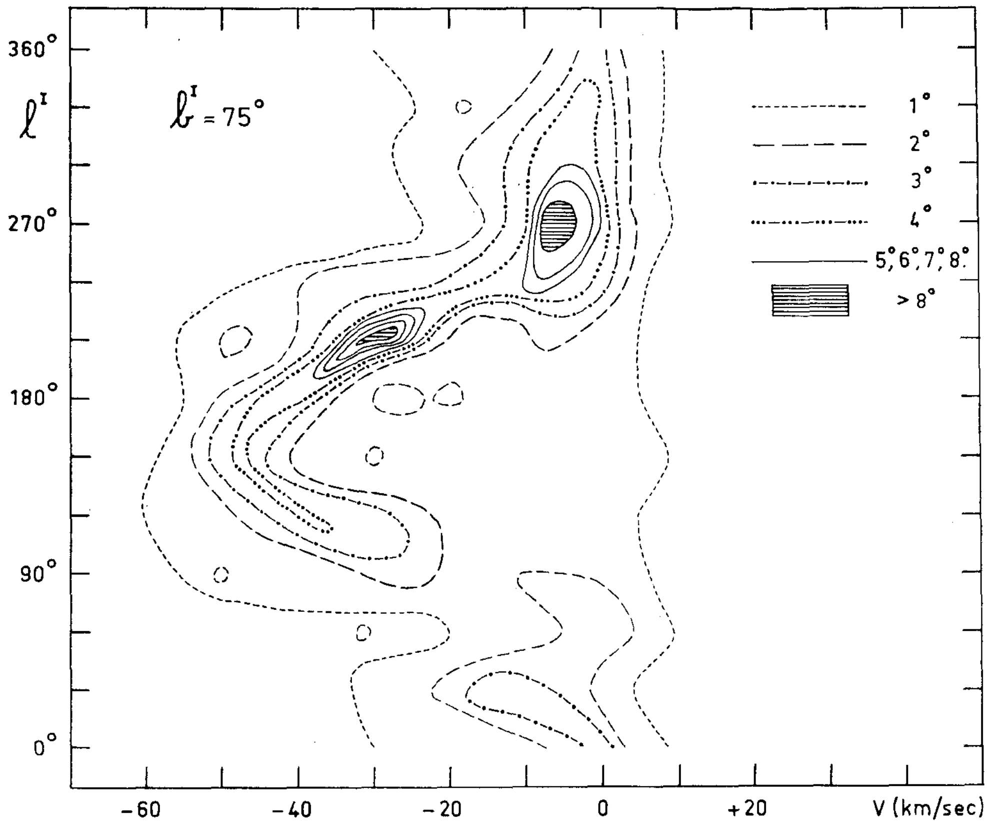

Fig. 11. *Velocities and intensities of the hydrogen layer at* +75° *galactic latitude.* (After an unpublished investigation by A. Blaauw and C. M. Tolbert).

An interesting phenomenon, which has been studied by Blaauw and Tolbert, is probably connected with such a stream. They found that at very high latitudes a local layer of hydrogen which was originally at rest, is apparently being pushed away by a cloud approaching with a velocity of about 60 km s^{-1} (cf. Figure 11). Somewhat similar results were found by Mrs

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Dieter, who observed at Harvard the galactic polar caps above $\pm$ 80° latitude. In the North-polar cap she found two sets of velocities, one between 0 and -10, the other at an average velocity of about -35 km s^{-1}. These observations indicate clearly that gas is streaming towards the galactic plane; about 40 % of the total amount of gas observed is flowing in at a relatively high velocity (*Astr. J.*, **69**, 288, 1964).

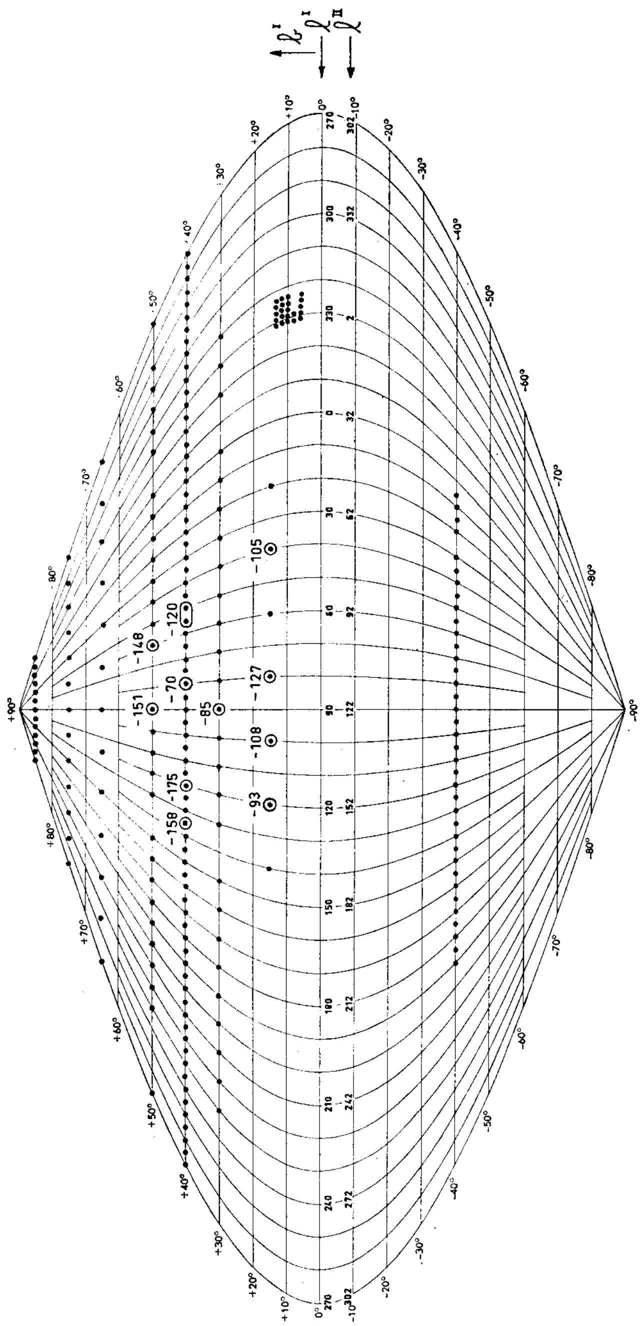

Fig. 12. *Distribution of clouds with radial velocities higher than 70 km s^{-1} relative to the local standard of rest.* The dots indicate the positions surveyed for high-velocity clouds (after an unpublished investigation by A. N. M. Hulsbosch, E. Raimond and J. H. Oort).

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The systematic behaviour of the high-latitude gas persists down to rather low velocities. But a specially intriguing feature is that some clouds with quite high velocities, up to 175 km s^{-1}, also seem to be connected with these streams. This indicates that the original velocity of the streams must have been very high. Figure 12 shows the distribution of the velocities higher than 70 km s^{-1} found in the high-latitude survey. It should be mentioned that it does not include the two high-velocity features found in the survey by Shane, which I have mentioned earlier; these features *may* be of a different nature.

The high-velocity clouds plotted in Figure 12 are all moving towards us, and are, moreover, concentrated in a small part of the sky, around a longitude of about 120°. Pretty much the same distribution is shown by the clouds with velocities between about -50 and -80 km s^{-1} found in an extensive survey made by Groningen astronomers between 10° and 25° latitude. These clouds also are sharply concentrated between 100° and 140° longitude.

XV. *Origin of the high-velocity clouds*

21-cm Observations can give no indication of the distance of features whose motions deviate greatly from the rotational motion of the Galaxy. At present any conclusion concerning the nature of the high-velocity features must therefore remain highly speculative.

We might suppose that the high-velocity gas is part of a supernova shell like the Cygnus loop. The shell would have to be very close by, not much farther than 50 pc, to explain the wide distribution over the sky. What makes the hypothesis unattractive is that not a single trace of the far side of the shell has been found, that no optical features have been observed in the high latitudes concerned, and that, unless the distances are improbably small, the total mass is too high. Moreover, the phenomena observed in the highest latitudes by Mrs Dieter and by Blaauw and Tolbert would seem to preclude an interpretation by one single supernova shell.

The alternative to interpreting the high-velocity clouds as a close-by supernova shell is to suppose that they represent gas flowing into the galactic layer from outside. In this case they must be expected to lie at distances of the order of a kiloparsec, and their masses must be of the order of a thousand times that of the Sun.

They could then either have originated in an outer region of the galactic disk, and represent part of a stream of gas ejected from an outer arm into the corona and falling back into the local arm, or a similar stream which is passing by. Finally they could also come from extragalactic space.

In the first case we would have to conclude that very massive clouds could be ejected by objects situated in an outer spiral arm. The total mass expelled would have had to be at least of the order of 10^5 solar masses. As this interpretation necessitates the supposition of a hitherto unknown phenomenon, it seems worth while to consider briefly the consequences of the alternative possibility that the high-velocity gas comes from outside the Galaxy. The clouds should in this case have fallen into the Galaxy. In doing so they would have acquired velocities of the order of 550 or 600 km s^{-1} relative to the local standard of rest. As their present velocities are about five times lower, they must have been decelerated by sweeping up gas either in the corona, or in the outer fringes of the galactic layer. The high-velocity clouds have such low surface densities that they are difficult to observe, even with the most sensitive receivers. Presumably the original, non-decelerated clouds would all be below the limit of detection. Only an order-of-magnitude estimate can be made of the flow of matter at large distances of the Galaxy which would be needed to yield the flow indicated by the high-velocity clouds. The outside gas density required would be of the order of ten times the critical density in the expanding universe. In view of the irregular distribution of matter in the universe this is not impossibly high.

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The most interesting consequence of a possible inflow of matter from intergalactic space would be that a relatively large accumulation of this matter should then be expected near the nucleus of the Galaxy. Due to the strong concentration of mass near the galactic centre the accretion factor would be an order of magnitude higher than in our region of the Galactic System. A rough estimate indicates that the inflow into the nuclear disk may then be of the same order as the outflow through the expanding arms. It is indeed tempting to think that inflow from extragalactic space might provide a mechanism for collecting gas in the nuclei of galaxies.

However, the observations made to date are still much too incomplete to give a sound basis for these speculations. Further observations may very well show that the phenomena described should be interpreted in a totally different manner.

Actually, we had set out to discover the gaseous corona of the Galaxy. We have, however, found totally different phenomena, and we know as little as before what the real corona is like.

In summarizing this lecture I remark that we seem to understand something of the main features of the distribution and motions of the *stars*, and we may even have the feeling that we have some sort of a picture of how the system of stars may have been born and how it has evolved. Furthermore, we can understand why the interstellar gas is concentrated in a thin layer and why it rotates. But *there* our understanding of the behaviour of the gaseous component ends.

We do *not* understand the origin of its spiral structure, nor even the way in which this structure is maintained.

We do not know what causes the gas in the central region to move away from the nucleus, and why the gas density is so much lower within 4 kpc of the centre.

We do not know why the matter in the fast rotating nuclear disk appears to be in a different state from what we find elsewhere, nor why this disk has such a remarkably sharp outer boundary.

We do not know what the galactic corona is made of, nor how the remarkable systematic motions of the gas off the galactic plane are to be interpreted.

We seem to be standing once more at the door of a world in which we *see* marvellous phenomena but do not understand them. We astronomers are irresistably drawn toward this exciting world just because of its enigmas.

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