OBSERVATIONAL EVIDENCE FOR GALACTIC SPIRAL STRUCTURE

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Does our Galaxy possess spiral structure and, if so, can this structure be traced observationally with some degree of confidence? This is the major question to which I shall address myself tonight. Following my talk, Professor Lin will speak about the theoretical aspects of spiral structure. I shall be very brief in my references to spiral structure in galaxies outside our own and leave it largely to Professor Lin to speak about observations on other spiral galaxies and their relevance for possible theoretical interpretations.

A year ago, my good and distinguished friend Professor B. A. Vorontsov-Velyaminov chided me in his address at the Basel Symposium for having been too eager to accept the fact that observation suggests that our Galaxy really possesses spiral structure. I hope to show in my Discourse that for our Galaxy we have indeed evidence for the presence of an underlying structure of spiral features.

1. Introduction

In the 1930's it seemed like an almost hopeless task to undertake the tracing of the spiral structure of our Milky Way System, but a real breakthrough came in the late forties when Baade and Mayall [1] reported results of their studies relating to the spiral structure in Messier 31. They found that the spiral arms in that galaxy were most clearly traced by the emission nebulae and by the cosmically young O and B stars. Clusters and associations of O and B stars were especially helpful in outlining the spiral structure. Baade called on astronomers to examine in our Galaxy the distribution of O and B associations and their nebulosities. The challenge was accepted by W. W. Morgan of Yerkes Observatory, who, in 1951, with two of his then young students, Donald Osterbrock and Stewart Sharpless, presented the first over-all picture [2]. They found three parallel sections of spiral arms clearly delineated. These are, first, the arm in which our sun is located, the Orion Arm; next, a portion of a parallel outer arm, the Perseus Arm, about 2500 parsecs farther away from the center of our Galaxy than the Orion Arm; third, a section of an inner arm, the Sagittarius Arm, 1500 to 2000 parsecs closer to the center than the Orion Arm.

Figure 1 shows the Morgan-Osterbrock-Sharpless diagram brought up to date; it includes data from both the northern and the southern hemispheres. The diagram is based on the work of Wilhelm Becker and R. Fenkart of Basel and of Th. Schmidt-Kaler then of Bonn [3]; the diagram shows the positions in the galactic plane of the

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clusters and associations with O to B2 stars and of the associated emission nebulae. The three sections of spiral arms found by Morgan are shown rather neatly, and it is on the basis of this sort of diagram that Becker asserts that the 'pitch angle' of the three spiral arms averages close to 25°; here the pitch angle is defined as the angle between the direction of the section of a spiral arm and the direction of circular motion.

Early in 1951, radio astronomy began to stir. Ewen and Purcell [4] had followed up H. C. Van de Hulst's suggestion and they had discovered the 21 cm line of neutral atomic hydrogen. It became soon evident that we had a new way for the study of the hydrogen gas in the far parts of our local spiral arm and also in distant spiral features, some of which are hidden from the optical astronomer's view by the intervening thick cosmic dust clouds.

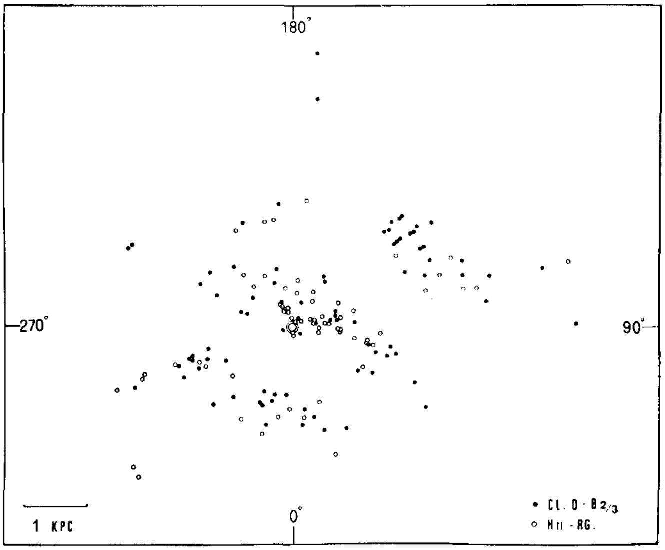

Fig. 1. Optical spiral structure of our galaxy. The Sun is at the center of the diagram. The galactic center is in the direction toward 0° galactic longitude at a distance of 10 kiloparsec from the Sun. The principal observed sections of the Sagittarius, Orion, and Perseus arms are shown. Original diagram by W. Becker and Th. Schmidt-Kaler, 1964; see B. J. Bok, *Am. Sci.* **55** (1967), 376.

The early work on the radio spiral structure of our Galaxy consisted principally of interpreting 21 cm profiles of neutral atomic hydrogen for directions spaced evenly along the band of the Milky Way. In the original interpretation of these profiles by the radio astronomers in Leiden and in Sydney, the assumption was made that there exists a single well-defined rotation curve of circular velocities for our Galaxy. This simple approach had soon to be revised, and the analyses made five to ten years ago were generally based on the assumption that rather different curves must be used for the interpretation of northern and southern hemisphere observations. The differences are now generally interpreted as being the consequence of large-scale streamings associated with the different spiral features.

The basic papers for the outline of the radio spiral structure of our Galaxy are those published by the Leiden [5] and Sydney [6] groups. The early results have been summarized by Oort, Kerr and Westerhout [7]. The most recent summary of the situation has been presented by Kerr [8]. Figure 2 shows the diagram prepared by Kerr and Westerhout, based in part on work by J. V. Hindman and A. P. Henderson; it is in essence the diagram shown at Basel by Kerr of the radio spiral structure of our Galaxy from 21 cm profiles.

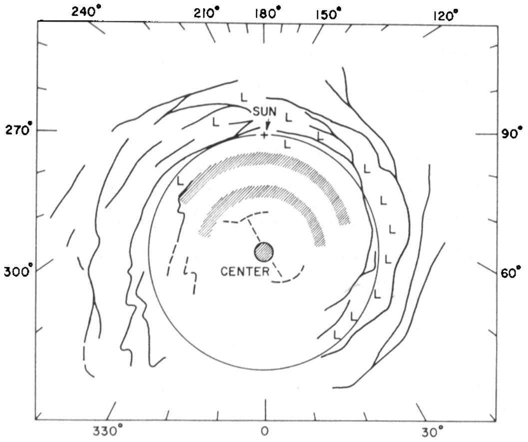

Fig. 2. The radio spiral structure of our galaxy. A sketch of the main features of the neutral hydrogen spiral structure prepared by Kerr and Westerhout. *L* indicates regions of low H I density.

The most exciting event of the Basel Symposium of a year ago was the presentation by Weaver [9] of a large amount of new 21 cm material gathered at Hat Creek Radio Observatory and the new spiral diagram drawn by Weaver as the result of his analysis of the old and the new data. Weaver's diagram of spiral structure is shown in Figure 3 and we note that his diagram differs radically from the Kerr-Westerhout diagram. Whereas Kerr and Westerhout prefer average pitch angles of the order of 5° to 7° for their spiral features, the Weaver picture suggests an average pitch angle of the order of 12°.5. I shall wish to return later in this talk to the Kerr-Westerhout and to the Weaver diagrams.

2. Spiral Structure in Messier 31

The spiral structure of a galaxy remains a beautiful, yet elusive feature. Part I of the Basel Symposium, covering 90 pages of text in the Symposium Volume, is devoted wholly to observational studies of the spiral structure for galaxies other than our own and many disturbing irregularities come to the fore. I shall not discuss these tonight, since Professor Lin will consider at some length special problems for different varieties of galaxies. But let me remind you that even our closest neighbor, the Great Andro-

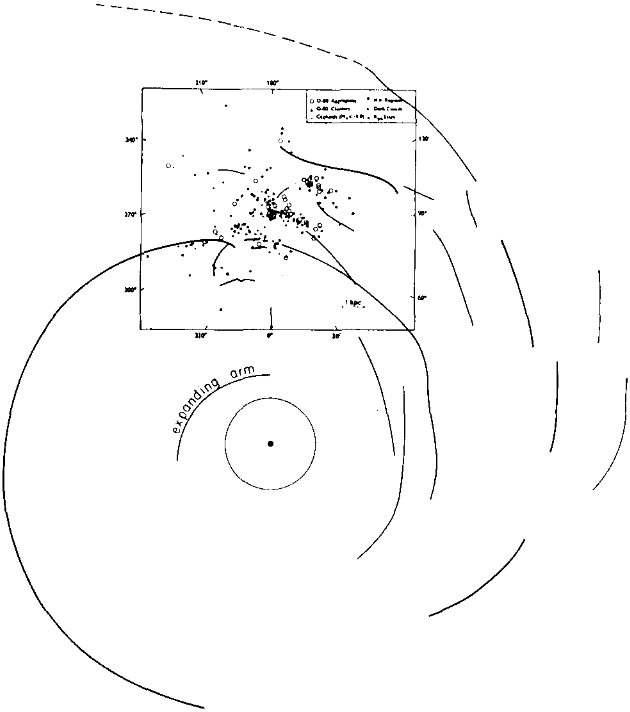

Fig. 3. Weaver's diagram of galactic spiral structure. The observed local distribution of young stars (see Figure 1) is superimposed upon Weaver's spiral pattern as derived from his analysis of the Hat Creek H I survey and other available H I profiles.

meda Galaxy, recognized as one of the finest of spirals, has some properties that do not fit into a sweet and all-inclusive spiral picture. In a study, published in 1964, Arp [10] re-analyzed some of Walter Baade's material on the spiral structure of Messier 31. He rectified the photographs and drawings for tilts in the range $i = 11°$ to $i = 16°$. The emission nebulae found by Baade gave patterns that could be adjusted to logarithmic spirals, but the basic pattern Arp finds has almost a closer resemblance to a ring-structure than to true spirality! And yet – no one can doubt that the basic pattern for the distribution of the ionized hydrogen in Messier 81, for example, is that of a delicate spiral structure, even though branches and bi-furcations present themselves in abundance.

Roberts [11] has compared the shapes of the H I contours with the Baade-Arp distribution of H II Regions. He finds basically very good agreement between the peaks of the H I contours and the Baade-Arp peaks of distribution of H II Regions. However, there is a suggestion of a bothersome shift between the two distributions. Rubin and Ford [12] have shown that, along the major axis of Messier 31, the H I maxima found from the survey of Burke *et al.* [13] correlate well with the maxima in the numbers of H II Regions of Baade-Arp. In an as yet unpublished investigation D. H. Rogstadt finds for Messier 101 that the optical and H I spiral arms coincide quite well. Hence we may assume for the present that radio H I and optical spiral arms coincide.

3. Basic Problems of Our Galaxy

Let us now return to our own Galaxy. Before we embark on a description of its spiral features, we should remind ourselves of the really limited knowledge that we possess of some of the basic properties of our own stellar system. At the Brighton General Assembly, we had a Joint Meeting of five Commissions to discuss the problems of mean absolute magnitudes and dispersions for the RR Lyrae variable stars, and also a special meeting of Commission 33 devoted to the distance scale of our Galaxy. There is still an uncertainty of 10 to 20% in that distance scale. As a result of our lack of precise information on the distance to the center and related uncertainties in the constants of galactic rotation, we have no really reliable curve relating the Circular Velocity, θ_c, with, R, the distance from the galactic center. As we shall see later in this address, we are only just beginning to obtain information on deviations from circular motion; however, already we possess good evidence for large-scale, local, streaming effects of the order of 10 to 30 km sec^{-1}. We are obviously uncertain about many basic properties of our Galaxy.

For our studies of spiral structure, the problems of the galactic magnetic field and those of the gas dynamics of the interstellar medium loom big. For the present it appears that the longitudinal fields have vectors aligned with the spiral features or arms. 21 cm data show that the ratio between arm and inter-arm gas density varies from 3:1 in the interior parts, according to Burton and Shane [14], to 10:1 in the outer parts, according to Kerr and Westerhout [15]. The indications are that the inter-arm gas is much hotter than the H I gas in the arms.

4. Spiral Tracers

Table I lists the recognized spiral tracers and we show in Table II a listing of the principal observational techniques now in use for applying them in studies of galactic spiral structure.

TABLE I

Spiral tracers

Optical	Radio
1. O and B stars-clusters-associations	1. 21 cm profiles
2. H II regions	2. Recombination lines notably H 109-α
3. Interstellar Clouds-absorption lines	3. Continuum edges synchrotron and thermal
4. Cepheids $P > 13^d$; $M_V < -4.5$	4. Absorption features 21 cm and molecular
5. M supergiants	
6. Be and WR stars	
7. Dark nebulae	
8. Polarization vectors	

TABLE II

Observational techniques used for spiral tracing

Photometric	Kinematic-optical	Kinematic-radio
1. Spectral-luminosity classification	1. Radial velocities of distant stars (image tubes!)	1. 21 cm profiles
2. Broad band photometry UBV-RI-longer	2. Radial velocities for H II regions (image tubes; interference techn.)	2. H109-α (and other recombination lines)
3. Intermediate band	3. Absorption line velocities (échelles; coudé; image tubes)	3. Line-features: (a) 21 cm absorption (b) Molecular lines in emission and in absorption
4. Narrow band and scanner		

The H II Regions and the O to B2 stars, singly, in clusters, or in associations, obviously continue to head the list. Photometric distances to O to B2 clusters and associations have figured prominently in all optical researches on spiral structure and the latest Becker and Fenkart diagram [16] is based exclusively on these objects and H II Regions. It has not proved difficult to apply the necessary corrections for interstellar absorption from reddening data for each cluster or association. The search by color techniques for very distant O to B2 stars (to $V=16$ or 17) is being pressed; in many low-absorption sections of the Milky Way O to B2 stars at distances of 8 to 10 kiloparsecs can now be located and studied [17]. In recent years, increasing emphasis has been placed on radial velocity determinations for the O to B2 groupings and the associated H II Regions. The radial velocities for O to B2 stars in clusters and associations can now be measured with ease and these, combined with the precision photometric distances for the same groupings, provide important basic information regarding the kinematics of our Galaxy, especially its rotation curve. We also have available beautiful recent data on radial velocities for H II Regions. Optically these have been measured especially by Courtès *et al.* [18], and earlier by Cruvellier, all of Marseille; by Miller [19], then of the University of Wisconsin; and by Smith [20] of Kitt Peak National Observatory, now at Cerro Tololo Interamerican Observatory. To supplement the optical data, we possess now the radio H109-α hydrogen radial velocities, which have been determined in abundance by Mezger *et al.* [21], for the southern Milky Way and by Reifenstein *et al.* [22] for the northern Milky Way. The combined radio and optical radial velocity material for H II Regions and associated OB stars is indeed in good shape for kinematical analysis.

In the years to come radial velocities for interstellar absorption lines, measured by optical and by radio techniques, will undoubtedly assume increasing importance.

The early work of Munch [23] showed the power for spiral structure research of analyses based on interstellar absorption line velocities and much more can be done now than was possible fifteen or more years ago. Coudé spectrographs fitted with image conversion tubes are now in operation on many telescopes, north and south, and Echelle spectrographs and spectrum scanners are rapidly becoming standard equipment for large telescopes. Hence, there is no reason why we should not be able to gather during the next few years extensive material on optical interstellar line intensities and radial velocities. The Marseille observers have begun important work in this area through observations with the La Silla Coudé telescope in Chile.

In the radio range, we now have a wealth of molecular interstellar lines to depend on. Our listings of radial velocities for these features produce important kinematical information, which can be turned to good use in studies of spiral structure. We note here that absorption features in 21 cm profiles have already assisted materially in eliminating distance ambiguities for some major H I features; molecular absorption lines should be similarly helpful.

With the rapid advances in infrared techniques of detection and measurement we may look forward to increased emphasis on red supergiants as possible spiral tracers. It has long been realized that a classical cepheid with a period of 13 d has a probable age of the order of 2 or 3 times 10^7 yr. Such objects will probably have been formed mostly in spiral features, and most of them should not have moved from their places of origin by much more than 200 parsecs; most of the displacement is likely to be along the spiral feature. Normal red giants, and cepheids with shorter periods, ages of the order of 5×10^7 yr or greater, may by now already be at 500 parsec, or more, from their places of origin, and their usefulness as spiral tracers becomes somewhat dubious. Long-period cepheids can be detected and observed to great distances from the sun, far beyond the distances to which O to B2 stars can be discovered. Kraft [24] has especially called attention to their potential as spiral tracers; the recent work by Tammann and Sandage [25] and by Gaposchkin [26] has strengthened their claim to a prominent place on our list of spiral tracers. The discovery of additional cepheids by photography is quite straightforward and, with the aid of modern photoelectric techniques, it should not be difficult to obtain good color curves and light curves for many faint cepheids. From such material it is quite simple to obtain fair estimates for the amount of intervening interstellar absorption and we may then derive reddening-corrected photometric distances for each of these stars. I expect that much useful information will come from photoelectric studies of long-period cepheids for directions along the galactic plane where the radio observations show the presence of many H II Regions that are not observed optically. Cepheids as distant as 10 kiloparsec and with five to seven magnitudes of intervening galactic absorption between the Sun and the stars are within reach. It should even not be difficult to determine their radial velocities provided this seems worth the effort. We note finally that the M-supergiants are bound to become increasingly more important as spiral tracers. The recent work by Humphreys [27] and by Lee [28] has shown that it is quite possible to obtain useful distance determinations for these stars up to distances of 6 to 8 kiloparsec from the Sun. The concentration of the M supergiants to the known spiral features, north and south, is shown especially well in the spiral diagram of Roberta Humphreys, Figure 4. Combined radial velocity and photoelectric research is obviously of great importance.

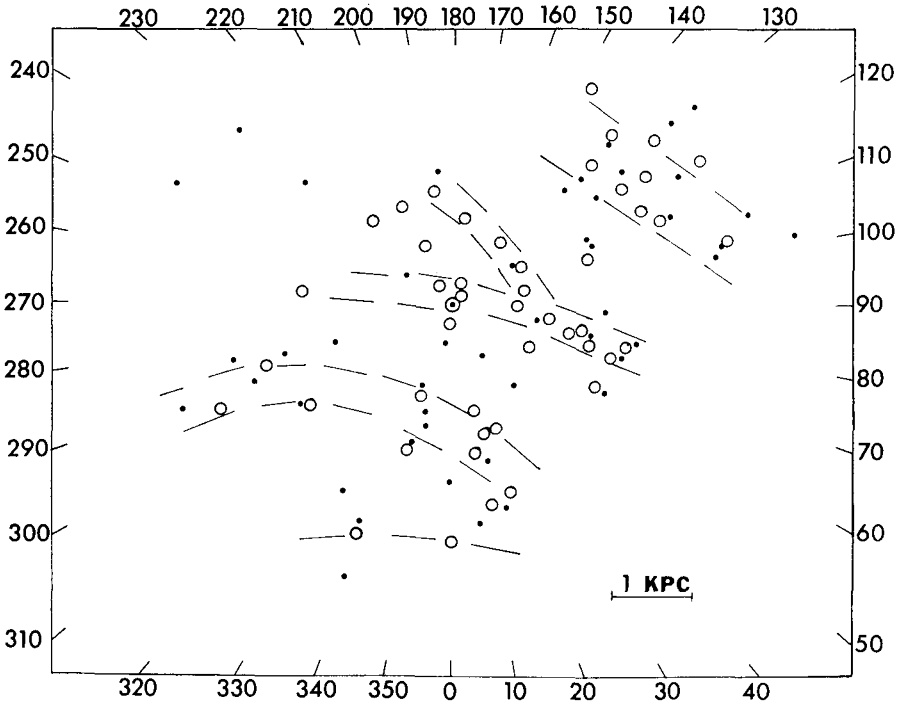

Fig. 4. Supergiants and spiral structure. The space distribution of stellar associations (open circles) and open clusters (dots) with Ia, Iab and Ib supergiants of all types is shown. The major spiral features are sketched and the position of the Sun has been marked. Diagram by Humphreys [27].

In galaxies outside our own dark nebulae show distributions which indicate a close affinity to the underlying spiral structure. Lynds [29] reported at the Basel Symposium on some very useful observed trends for the distribution of obscuring material relative to luminous spiral features. Figure 5 shows a fine example of her art. The most important trends are that dark matter is found apparently in abundance at the insides of most spiral arms and that the HII regions are generally imbedded in dust. In the interior sections, some luminous spiral arms are found to be channeled between dark lanes. The picture is not clear for our own Galaxy, where dark matter is found mostly at the insides of the observed spiral features, but by no means exclusively so.

Two varieties of stars appear to give further data relating to spiral structure. The work of Schmidt-Kaler on Be stars [30] and that of Smith [31] on Wolf-Rayet stars has shown that much useful information can be derived from diagrams showing the distribution of these stars in the galactic plane.

Most other observed varieties of stars are too old by cosmic standards to be useful as spiral tracers. Late B stars, A stars and early F stars may be used effectively as tracers of fossil spiral structure, since they had their origins in earlier stages of development of our Galaxy. The study of their motions, especially through investi-

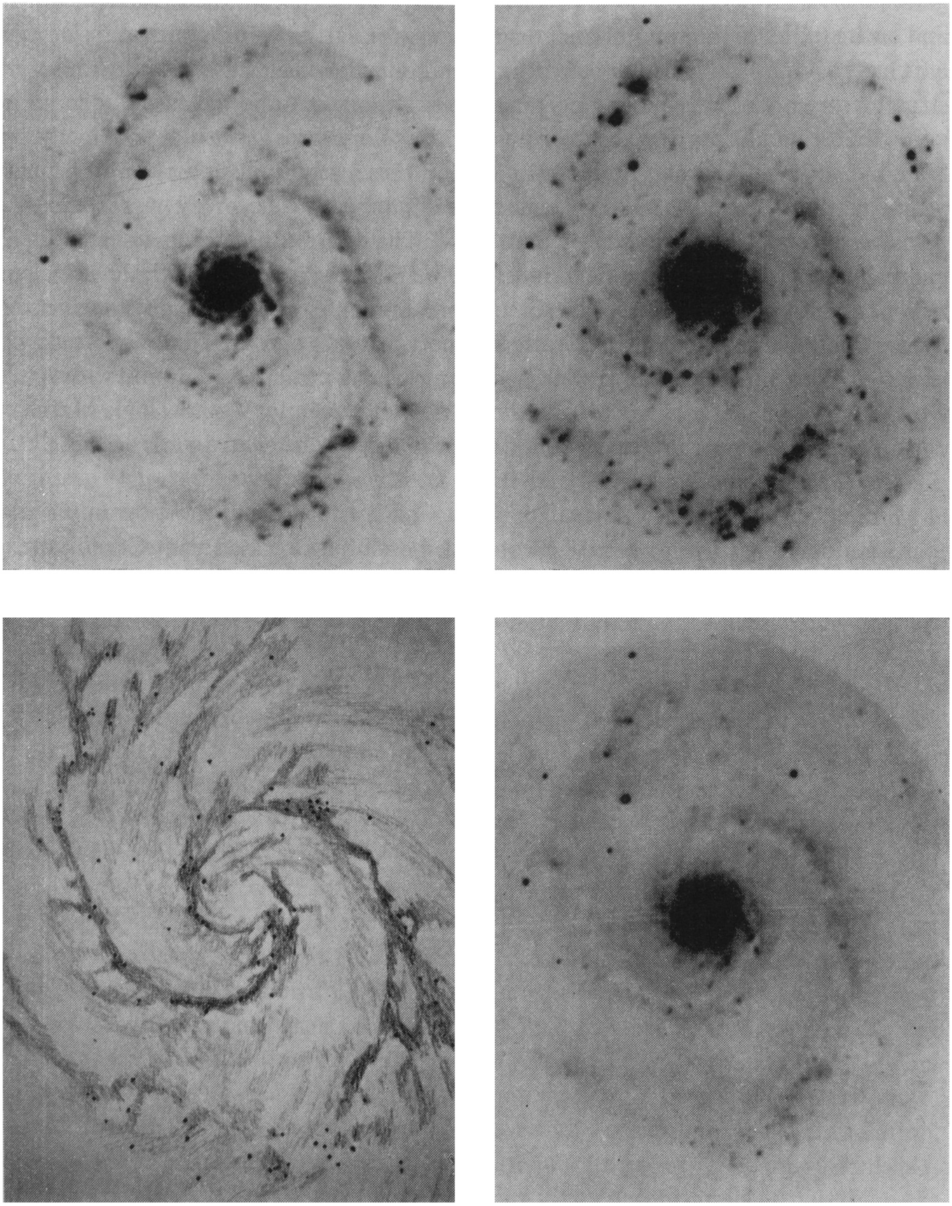

Fig. 5. Messier 51. The two photographs at the top represent an exposure through a broad-band blue filter (left-top) and an Hα filter (right-top). The photograph in the lower right was obtained by exposing through a narrow red filter (eliminating Hα) centered at $\lambda = 6650$ Å. The drawing in the lower left is based upon a long exposure with the 200-in. Hale Reflector on Palomar Mountain (Humason); Dr. Lynds has drawn the dark lanes by proper shading and the H II Regions are shown by black dots. Material from the paper by B. T. Lynds (1971; (29)); photographs made with the Steward Observatory 90-in. Reflector.

gations of vertex deviation, yields very useful information about their places of origin and such studies help pinpoint anchor positions for earlier spiral structure.

It has become established in recent years that magnetic fields associated with spiral structure are not of as major importance as was thought to be the case fifteen years ago. The original data for the Northern Milky Way were gathered principally by Hall and Mikesell [32] and by Hiltner [33] and these were quite complete. For many years our knowledge of polarization for the Southern Milky Way was limited to results from a single early study by Smith [34]. The data seemed to suggest that there generally exists a longitudinal field, in which the *E*-vector is aligned with the principal axis of a spiral feature. There was some confusion as to whether or not the average percentage polarization increases with distance from the sun as rapidly as would be expected. This simple overall picture has been severely criticized by Mathewson [35]. Much additional material has become available quite recently. We now have Mathewson's new data, shown in Figure 6, and the information presented at the Basel Symposium by Klare and Neckel [36].

Mathewson has analysed all available data and it appears that the most important contribution comes from a local helical field, possibly associated with Gould's Belt.

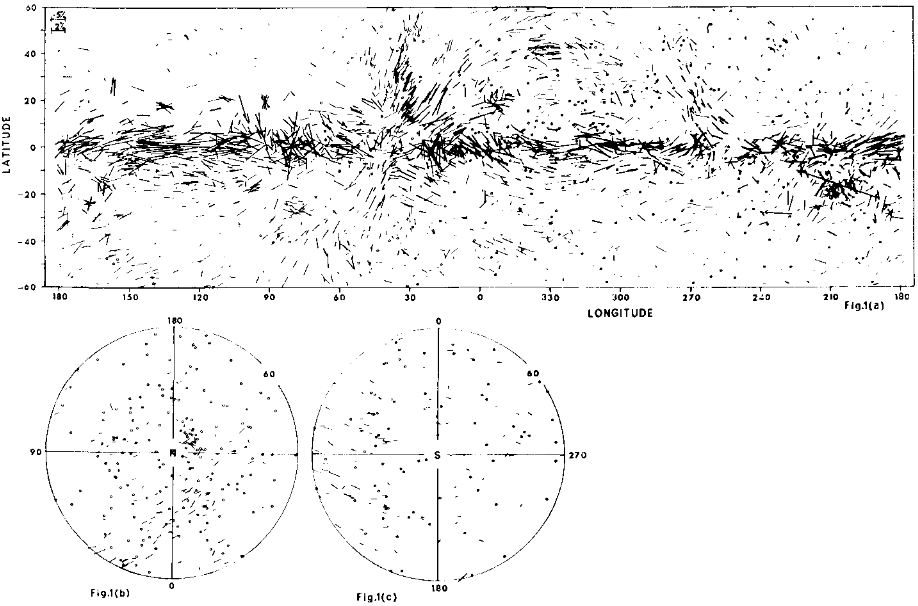

Fig. 6. Optical polarization. The Diagram summarizes all available data on interstellar galactic polarization. It is from a paper-in-press to be published by Don S. Mathewson in the Memoirs of the Royal Astronomical Society. The plot shows the *E*-Vectors of polarization, and represents data for 7000 stars. Measurement for 1800 stars were made by Mathewson at Siding Spring Observatory; the remainder are from the Catalogs by Hall, Hiltner, Behr, Loden, Appenzeller, Visvanathan and E. van P. Smith. The *small circles* mark the positions of stars with percentage polarization, $P < 0.08$. The vectors for the stars with $0.08 < P < 0.60$ are *drawn thin* (top scale), and the vector for the stars with $P > 0.60$ are *drawn thick*.

In addition he has good evidence for a major longitudinal field, which is probably the basic field associated with the spiral structure. Mathewson points out that this model satisfies not only the optical data, but also the material on radio-background polarization, synchrotron brightness distribution, Faraday-rotation data on extragalactic radio sources, Zeeman and pulsar observations. Mathewson's interpretation has been questioned by Gardner *et al.* [37] and the whole situation has been reviewed by Verschuur [38] in a summarizing paper presented at the Crimean Symposium; Verschuur accepts the Mathewson model. From the available evidence it does seem that effects produced by helical fields are important, but, when all is said and done, there does remain the fundamental observed trend that approximate parallelism of *E*-vectors is observed over large sections in galactic longitude, and that confusion reigns in other sections. The data seem to suggest that in the case of parallelism we are observing across a spiral feature, and along one in the case of confusion.

The longitudinal field averages in all probability only 2 or 3 μG in strength. Ten to fifteen years ago, the trend was to consider seriously the hypothesis that galactic spiral structure is caused by large-scale magnetic fields, which would align the gas in spiral patterns. The weakness of the observed averaged magnetic field rules out such a state of affairs. Now it seems more likely that gravitational forces are responsible for the observed large-scale spiral patterns and that the magnetic fields are frozen into these patterns as a by-product of the distribution of the ionized gas. Gravitational concentration of the ionized gas may locally produce magnetic fields of unusual strength. The observed pattern of longitudinal and parallel polarization vectors is thus considered a by-product caused by the concentration of ionized gas in spiral features. In spite of the obvious complexity of the situation, I consider the future detailed analysis of optical polarization data as one of the basic keys to the delineation of the spiral structure of our Galaxy.

In the radio range, we can learn from continuum studies a good deal about the underlying general structural features. Mills [39] showed many years ago that steps in the longitude distribution of continuum radiation at intermediate radio wavelengths, presumably synchrotron radiation, show a step distribution suggesting edge features of galactic spiral arms. A recent study giving evidence for a gap between the Carina and Sagittarius arms by Frank and Maureen Kerr, [40] based on 11 cm continuum data which must be of thermal origin, shows that important questions of spiral structure can also be resolved through study of continuum thermal radiation.

The latest arrival on the spiral-tracer scene are pulsars and X-ray sources. Mills [41] and Lynga [42] have drawn attention to the possible concentration of pulsars in the Local and Sagittarius Arms. However, the pulsars are still too few in number and they are generally too close to our sun to be of much use. We should also record that Prentice [43] has shown that the distances assigned by Mills are in error and that pulsars do not possess a distribution in our Galaxy related to the spiral structure. The X-ray sources are also not yet contributing to our basic knowledge of galactic spiral structure, even though they show a tendency to concentrate toward spiral features. This is shown especially well in a recent diagram by W. Haupt and Schmidt-

Kaler [44]; the absence of X-ray sources associated with the Carina-Centaurus spiral feature is rather puzzling.

In recent years, Schmidt-Kaler and Isserstedt [45] have attempted to show that stellar rings of the variety studied by them may yield much useful information on the overall spiral pattern of our Galaxy. I continue to be quite skeptical about their work. Some of the nearby objects which they consider as prime examples of their rings are O and B star groupings or small associations, and from the color magnitude studies of some of these rings Schmidt-Kaler and Isserstedt have obtained new and useful information about distances and intervening absorptions for these groupings. However, I am not ready to accept the geometrical approach suggested by these authors, which would assign unique major and minor diameters to all ring-like objects in our Galaxy. Hence, I am unwilling to accept their general diagram of spiral structure, which includes data for some objects supposedly at distances from the Sun of 15 and more kiloparsec in the direction of the galactic center!

5. Optical Spiral Structure

A few general comments are in order as we proceed to discuss the underlying spiral features of our Galaxy. Figure 7 shows a diagram that I have always found most

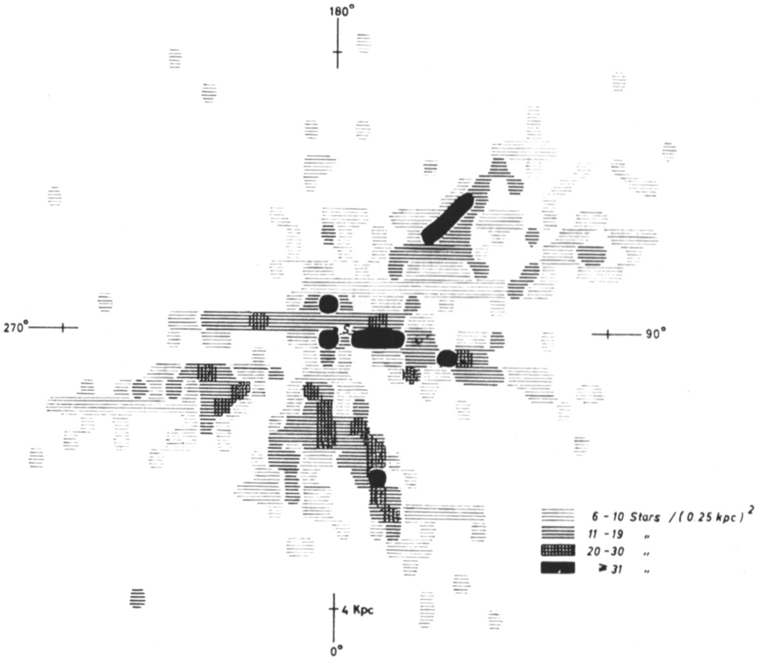

Fig. 7. Distribution of OB stars. The distribution of 5083 OB+ and OB° stars and of 1090 OB stars with known MK spectral-luminosity class is shown in projection on the galactic plane. The Sun's position is at the center of the diagram (Klare and Neckel, 1970, *IAU Symp.* **38**, 449.)

instructive. It is by Klare and Neckel [46] of Heidelberg and exhibits the distribution of high luminosity O and B stars. Their data cover both the northern and southern Milky Way and their distances are absorption-corrected ones. The diagram reaches to a distance of 4 kiloparsec from the Sun. This diagram shows how careful we must be before we start drawing spiral arms! There obviously exist four or five rather elongated concentrations of O and B stars. We see present what is generally referred to as the Orion Arm and a section of the Perseus Arm, also the Carina-Centaurus feature and an inner concentration from Scutum through Sagittarius to Norma. These features fit nicely into the Becker-Fenkart O and B cluster diagram, but one can fit them equally well into other diagrams for local spiral structure. In many respects, all of our connecting of concentrations into one master diagram represents a rather futile game. Available optical data generally do not extend beyond four kiloparsecs in the galactic plane and without data extending to at least 10 kiloparsec from the Sun we cannot begin to draw an overall spiral pattern for our Galaxy. We obviously require the radio data as well. However, the optical data do delineate neatly certain undoubted spiral features. There are the Cygnus-Orion feature, the Perseus feature, the Carina-Centaurus feature and the inner feature associated with the Sagittarius Arm.

Once a spiral feature has been located, we can make detailed ‘anatomical’ studies of its properties. My associates, Ellis Miller, Alice Hine and I [47] presented at Basel the first results of such a study for the Carina-Centaurus feature. At the same Symposium, Helène Dickel *et al.* [48] gave their results for a rather similar study on the distribution of H II Regions for the direction of the Cygnus feature. Anatomical studies can now be made for the Perseus feature, for the Orion feature, for the structure in Puppis Vela, for the Norma feature and for the Sagittarius and Scutum Arms. From such studies one can derive the width of the spiral feature in neutral atomic hydrogen and locate in this broad band the narrower strip of recent and current star origin shown by the O and B stars and by the H II Regions. The distribution of the cosmic dust relative to the general outline of each feature can be defined, and the associated magnetic fields may be studied. Basic items of information regarding the kinematics of spiral structure and the structural contents of each feature, as these relate to star birth and evolution, may be investigated. Such studies can provide new information for theories of the gas and stellar dynamics of spiral features and from such studies the theoretical astrophysicist can learn much that is new about the physical conditions under which stars are born and develop into spiral features. For example, it becomes clear that star birth does not take place more or less uniformly along a narrow ridge in the broader gaseous spiral feature, but rather that it takes place primarily in regions of well above average high-gas density, appearing as beads upon a string marked by a narrow ionization ridge.

I shall illustrate this approach in detail by showing some diagrams, Figures 8 and 9 relating to the feature in Carina-Centaurus which I know so well. The recent work of Graham [49] proves the presence of a sharp ridge of O and B stars that marks the outer edges of the Carina feature; this ridge had been drawn already in the past, notably by Sher [50]; it is also shown in the study by Feinstein [51]. The narrowness of the O and B stars – H II Regions – Ridge is shown well by these studies; the concentration of star birth along the ridge is exhibited by the young stars and by the plentiful interstellar ionized hydrogen. They are found in such groupings as those near the Great Carina Nebula and another near the nebula associated with IC 2944.

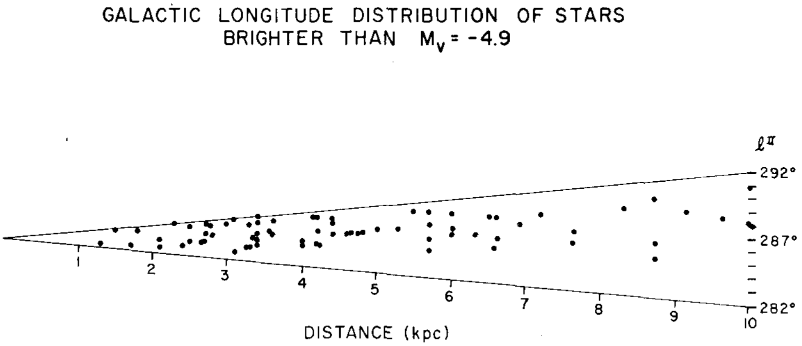

Fig. 8. OB stars in Carina. J. A. Graham's plot of the distribution in depth of the OB stars with $M_V \leqq -4.9$ in the Carina Section.

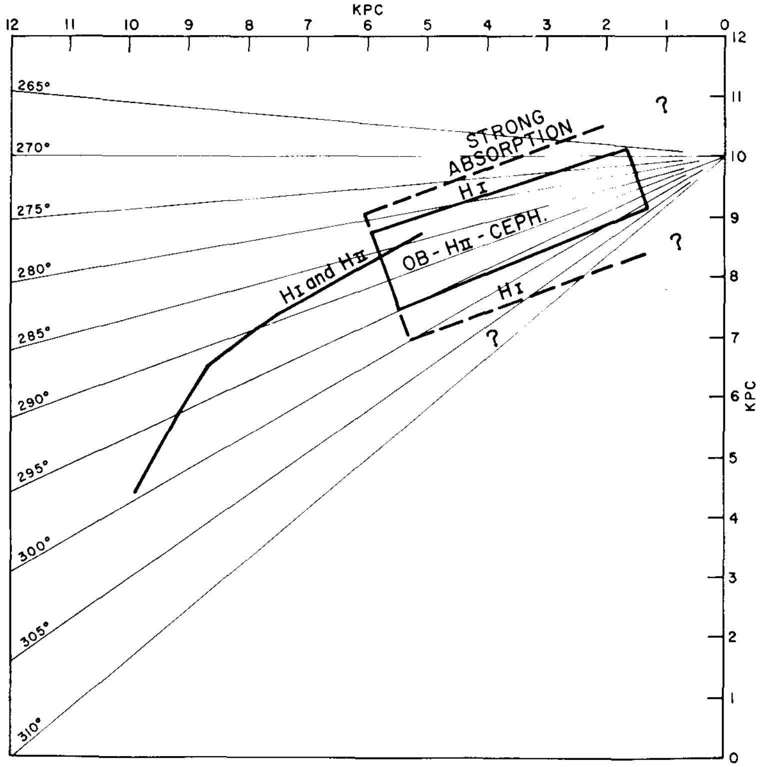

Fig. 9. A working diagram of the Carina spiral feature. According to Bok *et al.* [47].

An elongated concentration of long-period cepheid variables is found in Carina, precisely in the direction where we find the O and B stars and H II Regions concentration. We note that for the direction of the concentrations of O and B stars, emission nebulae and cepheids, we find relatively small galactic obscuration, but we find evidence for much cosmic dust on the side of the feature away from the galactic center. Figure 10 shows schematically comparable results obtained by Dickel, Wendker, and Bieritz, for the distribution of ionized hydrogen for the Cygnus direction. The distribution seems to define a section of an arm with the sun near its inner edge. We note that both the Carina-Centaurus feature and the Cygnus feature have local tilts with respect to the galactic plane of the order of 2°, or slightly greater.

At this point in the Discourse we should take the time to review the optical evidence regarding spiral structure of our Galaxy that we possess at this time. Three years ago I presented a brief listing of the Established Optical Spiral Features, which is reproduced in Table III, slightly updated.

More recently Courtès *et al.* [18] published their results on the spiral structure based principally on H II Regions and they list the four major sections of spiral arms shown in Table IV.

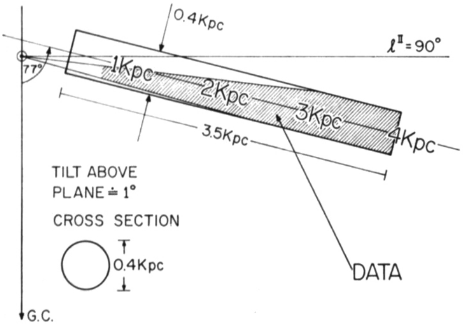

Fig. 10. A model for the local arm. A diagram resulting from a study of ionized hydrogen distribution in Cygnus by Dickel *et al.* [48].

TABLE III

Observed optical spiral features, Bok, 1967–70

Name	Range in Gal. long.	Min. distance to Sun
Perseus	90° to 140°	3 kpc
Local	60° to 210°	Sun at inside
Sagittarius	330° to 30°	2 kpc
Carina section	280° to 300°	1.5 kpc
Centaurus link	310° to 330°	1.8 kpc

Notes to Table III:

(1) Carina section is optically observed to a distance of 6 kpc from Sun.

(2) Puppis-Vela section is complex.

(3) Observed gaps: (a) $30° < l < 60°$ – (b) $270° < l < 280°$ – (c) near $l = 305°$.

TABLE IV

Observed optical spiral features
Courtès-Georgelins-Monnet, 1969

Name	Range in Gal. long.	Min. distance to Sun
Perseus	103° to 190°	3 kpc at 1 = 120°
Orion	59° to 254°	0.5 kpc at 1 = 180°
Sagittarius	274° to 32°	1.5 kpc at 1 = 330°
Norma	305° to 333°	3.5 kpc at 1 = 330°

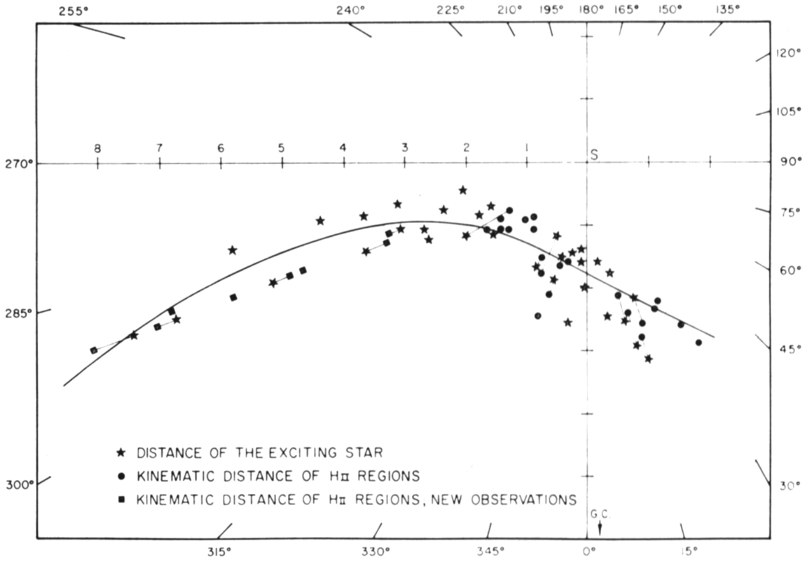

Fig. 11. The Sagittarius-Carina arm according to the Marseille results. From a paper by Y. P. and Y. M. Georgelin, *Astron. Astrophys.* 7 (1970), 139.

The French results are essentially in agreement with those presented at Basel by Becker and Fenkart.

To stress the importance of the work by the Marseille astronomers, we show in Figure 11 the Sagittarius-Centaurus-Carina Arm as drawn by the French group. In private conversation Courtès has emphasized that the continuity of the spiral feature is both a structural and a kinematic continuity. In other words, both the photometric distances of the exciting stars for the H II Regions, corrected for interstellar absorption, and the kinematical distances, derived from the radial velocities of the H II Regions, fit a single well-defined curve. There is a gap in the feature between $l = 313°$ and $l = 333°$ (new system of galactic coordinates) in which the French group finds only one weak optical H II Region over 700 parsec, but they note that Lynga [52] finds several inconspicuous young open clusters in this gap. The Marseille astronomers assign a pitch-angle of 9° to the Sagittarius-Centaurus-Carina Arm. This value is derived mostly from nine H II Regions near $l = 290°$, which I view as distant objects in the Carina Arm.

To what extent do we disagree? There are no basic disagreements regarding the Perseus Arm. I draw my upper boundary in galactic longitude conservatively at 140°, whereas the new French results show that features associated with the Perseus Arm are detectable to $l = 190°$. The section of the Milky Way beyond 140° is certainly exceedingly weak and it does not compare in strength with the clearly delineated main feature. We are in essential agreement in that we see a Local Arm, with the Sun at the inside or in the Arm, from Cygnus (60°) to Canis Major (210°). I grant that there are confused spiral features in the range between 210° and 254°, but I would hesitate to refer to them definitely as an extension of our Local Arm; some of the features in Puppis are quite close to the Sun, whereas others are about 5000 pc away from the Sun. The French astronomers, as well as Becker and Fenkart, also G. Lynga, lump together in one major Sagittarius Feature *all* O and B star clusters and H II Regions between galactic longitudes 274° and 32°. I am not at all certain that this approach will stand up in the end. We are agreed that there are two clear and clean features, one in Sagittarius, extending from 330° to 30° in galactic longitude, and another in Carina, between galactic longitudes 280° and 305°. I continue to emphasize that the Centaurus Link, 305° to 330°, is very weak indeed; the French astronomers and Lynga plot the weak features in Centaurus with symbols equally prominent as those representing the strong features in Carina and Norma. I think that we are all agreed that the work of Graham on the O and B stars and the available 21 centimeter data firmly support the presence of a sharp outer edge to the Carina feature at longitude 283°. The optical data seem to support an inner edge pointing more or less away from us near $l = 300°$. This edge is shown most clearly in the radio data discussed by Frank and Maureen Kerr [40]. The Norma-Scutum Arm (inside the Sagittarius Arm) is shown in the work by the French group to be detectable in the range $305° < l < 330°$; Kerr would place the objects in the range $305° < l < 325°$ in the Sagittarius Arm and he thinks that the Norma Arm is viewed tangentially at $l = 327°$, very much in line with A. D. Thackeray's original suggestion.

6. Kinematics of Gas and Stars

In recent years increasing attention has been given to the study of the kinematics of gas and stars associated with spiral features. The first suggestion of major streaming phenomena came from Kerr's [8] work on apparent differences between the rotation curves for our Galaxy as these were derived separately from northern and from southern hemisphere data on tangential H I velocities. The two curves, shown in Figure 12, diverge in places by as much as fifteen kilometers per second. At first some of us were tempted to accept as probable Kerr's interpretation in terms of a general galactic expansion, but this hypothesis did not prove tenable in the end. We now look upon these differences as caused principally by large-scale streamings of gas and stars, streamings which presumably originate because of a spiral potential field of the

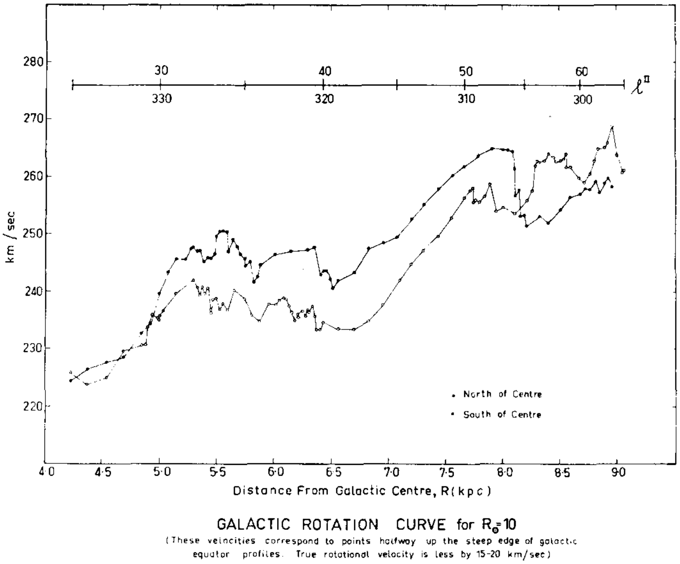

Fig. 12. Rotation curves for our Galaxy. Galactic rotation curves according to Kerr [8] for the halves of the Milky Way to the north (upper) and south (lower) of the galactic center. The curves are derived on the basis of tangential-point observations of H I profiles, assuming circular rotation and no streaming.

type envisaged by C. C. Lin and associates. Evidence for large-scale streamings have been found by Burton and Shane [14] for the Scutum Section, by Lindblad [53] for the Anti-Center direction and, most markedly, by Rickard [54] for the Perseus Arm. Further observational work by optical and radio techniques is obviously important. This should be done optically especially through the study of radial velocities of interstellar absorption lines.

One question that relates immediately to the radial velocity work is the extent to which stellar and gaseous radial velocities agree or differ at various positions in the galactic plane. Seven years ago Fletcher [55] had shown that no great differences exist for many points in our Galaxy. However, some years later, Dixon [56] found evidence for differences in velocity between gas and young stars amounting to fifteen kilometers per second. The Dixon results, which were somewhat uncertain because of possible errors in distance estimates, have not been confirmed and all of the current evidence seems to suggest that young stars and gas move together. The work of Feast and Shuttleworth [57] on cepheid variables in Carina shows this especially well, as does the work of Humphreys [27] on M supergiants. These results are of special interest since we would not expect agreement if galactic magnetic fields had a predominant influence on gaseous motions. The magnetic fields would not be able to affect the star's motions after birth and marked differences in velocity between gas and stars would be expected to accrue if the longitudinal magnetic field were to have a controlling influence on the motion of the gas.

It is interesting to remind you briefly that radio absorption and emission lines have been found associated with concentrations of cosmic dust. If the association of dust concentrations with hydrogen gas and with certain molecules can be further established, then it will become possible to measure radial velocities for dust clouds, and the study of their kinematics will then become a major new field for studies of spiral kinematics. Work along these lines is under way at the University of Maryland, where Jill Knapp has measured several dozen dust cloud velocities from H I – 21 centimeter self absorption; work on the kinematics of the dust system is in progress on the basis of these data and others for OH and CH_2O.

7. Radio Evidence from Continuum Studies and Recombination Lines

We have mentioned repeatedly that optically we are able to locate certain spiral features quite well, but that from them alone we cannot hope to obtain the spiral diagram of the 'Grand Design', desired by Professor Lin. For this we need the radio data. There are basically three radio approaches available for the study of the 'Grand Design'. The first of these is the Mills approach through edges in the continuum distribution. The second is through radio studies of distant H II Regions, in the continuum and especially through high-level atomic recombination transitions, such as the H109-α transition in neutral hydrogen. The traditional third, and still the most powerful approach, comes through the 21 cm line profiles of neutral atomic hydrogen.

The value of the study of continuum edges is often overlooked. The early results of Mills [39], based on synchrotron continuum radiation, gave evidence for an overall spiral pattern of our Galaxy with near-circular arms. The recent result by Frank and Maureen Kerr [40], to which we have already made reference, gives strong support to the assertion that the Carina and Sagittarius Arms are separate features of galactic spiral structure. They find a very low integrated flux of H109-α sources between galactic longitudes 295° and 305°, supported by a comparably low integrated flux for the 11 cm continuum.

The original surveys of the continuum radio radiation in the 20 cm range were made by Westerhout [58] and by Mathewson *et al.* [59]. This radiation is attributable to H II Regions close to or in the galactic plane and is of thermal origin. Since H II Regions are concentrated toward spiral features, it seemed likely from the start that the 20 cm continuum radiation would largely originate in spiral features. The early studies supported these conclusions, but it was evident from the start that the distribution of H I and H II is by no means identical. The early studies show already that H II is scarce in the outer parts of our Galaxy, which are rich in H I, and that there exists a strong concentration of sources of H II radiation in the belt three to five kiloparsec from the galactic center. The discovery of the radio-recombination lines, H109-α and others, helped confirm and strengthen these conclusions. The most recent work in this area was summarized by Mezger [60] at the Basel Symposium. The results appear in many ways far from encouraging for research on the spiral structure of our Galaxy.

The Giant H II Regions, as defined by Mezger, seem to be concentrated in a ring between 4 and 6 kiloparsec from the galactic center, and they do not seem to relate at all to the outer spiral structure. There are practically no Giant H II Regions beyond 12 kiloparsec from the center, whereas the surface density of H I reaches a maximum at 12 to 15 kiloparsec from the center. The Mezger pattern of structure for the distribution of all radio H II Regions with distances assigned on the basis of kinematical properties does not show any clear spiral pattern. However, we should bear in mind that in our Galaxy we find large-scale streamings of gas and young stars associated with spiral structure, and such streamings will of course affect the distance estimates based on kinematical considerations alone.

How shall we best make use of the radio data for the H II Regions? My first recommendation is that we make every effort to detect and study optically as many of these regions as are within reach of our large telescopes, north and south. The work by Courtès [18] and associates and by Smith and Weedman [20] shows that good optical data can be obtained now for very faint H II Regions.

Mezger suggests that many of his Giant H II Regions are so deeply imbedded in cosmic dust that they may be optically unobservable. However, if they are concentrations in major spiral features, then we may expect in their vicinity and associated with these features other spiral tracers, long-period cepheids, or supergiants and normal OB associations and related non-Giant H II Regions.

Combined photographic and photoelectric search techniques permit us to detect possible exciting O and B stars to great distances from the Sun, and their distances can be estimated with fair accuracy. Related studies of long-period cepheid variables and M, N, S supergiants can be made optically. Such work can yield photometric distances and associated radial velocities. I feel strongly that our hope for the future lies in attempts to trace spiral features through combined optical and radio research. As an example of such work I shall refer briefly to some recent work by Alice Hine. On the basis of our optical work on the Carina-Centaurus Section, she could assign reliable optical distances to quite a few of Mezger's H II Regions, and she finds that the Mezger H II Regions on her list fit nicely into the overall spiral pattern in Carina-Centaurus suggested by our optical data and by 21 cm line profiles.

8. 21 Centimeter Patterns; Conflicting Results of F. J. Kerr and J. F. Weaver

The interpretation of 21 cm profiles has in recent years become a more difficult and uncertain task than it seemed fifteen years ago, principally because we recognize now that the neutral hydrogen gas exhibits large-scale local deviations from circular motion. Some of these deviations arise probably as a consequence of the density-wave phenomena of the variety predicted by the Lin-Shu theory. The new approach is to predict by computation theoretical 21 cm profiles on the basis of reasonable assumptions regarding the density and velocity distribution of the H I gas. These profiles are then compared with the observed ones. Examples of this approach are in the recent papers by Yuan [61] and by Burton and Shane [14]. Professor Lin will discuss Yuan's work, and also that of Roberts [62], but we wish to draw here briefly attention to the results obtained in Burton's [63] latest paper.

Burton's work is based on model calculations. He starts out by assuming certain characteristics for the underlying velocity field for the section of our Galaxy under investigation. This velocity-field has non-circular components of the kind predicted by the Lin-Shu density-wave theory. He can then calculate the predicted H I distribution in the (l, V) field (galactic longitude versus radial velocity) applicable to the section of galactic longitude under investigation and compare with observations. One surprising result of Burton's model calculations is that slight variations in local streaming conditions may yield much more striking variations in the predicted 21 cm patterns than seem to result from reasonable variations in the H I density distribution.

Burton has considered in his studies only the first quadrant $0° < l < 90°$, especially has he tried to represent the observations for $40° < l < 90°$. The best fit between theoretical prediction and observation is found if he assumes the presence of three well-defined sections of spiral arms; (see Figure 13.) First, he notes that there are strong arguments in favor of the presence of a major Sagittarius Arm of well-above average H I density. Apparently we observe the Sagittarius Arm tangentially at $l = 55°$. The

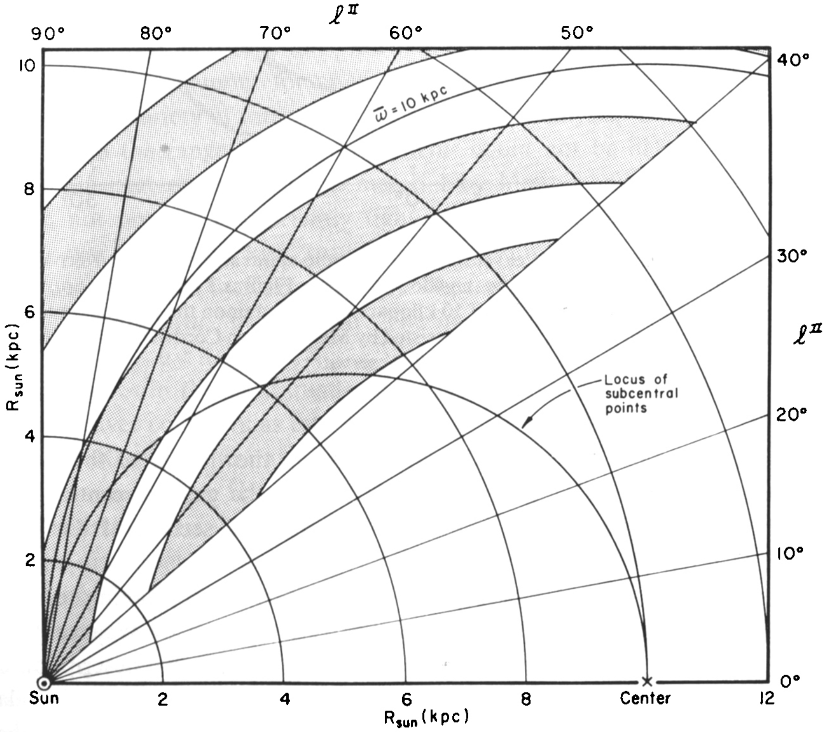

Fig. 13. The Burton diagram of spiral features. The diagram by Burton [63] shows a section of the Sagittarius Arm, the Cygnus Arm (emerging from the vicinity of the Sun) and a portion of the Perseus Arm.

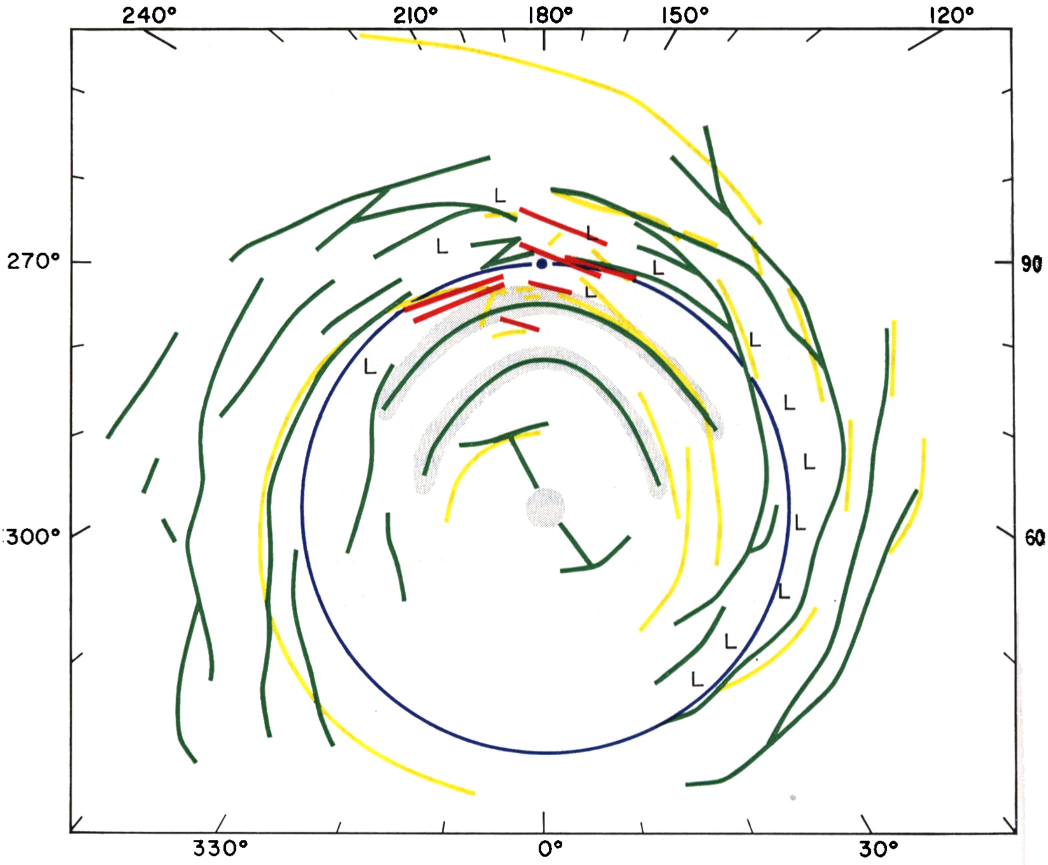

Fig. 14. The Kerr-Westerhout and Weaver diagrams of radio spiral structure. The Kerr-Westerhout diagram is shown in green, the Weaver one in yellow (compare Figures 2 and 3). The optical features are shown in red and a circle with a radius of 10 kiloparsec centered upon the galactic center is shown in blue. Diagram prepared by Mr. David Daer, assisted by Miss Carolyn Cordwell and Mr. Ed. Howell, all of Steward Observatory.

second arm, the Cygnus Arm, is seen emerging from the vicinity of the Sun in the range $60° < l < 90°$, gradually bending inwards toward the galactic center, clearly a trailing arm. Finally, the Burton diagram shows nicely a section of the Outer or Perseus Arm.

In the remaining part of my Discourse, I shall discuss the conflicting results from the analysis of available 21 cm data obtained by Kerr [8] and by Weaver [9]. Since so much of the material has not yet been published, and since the description of the details of much of Weaver's analysis is still lacking, it is difficult to present a balanced story and I find it impossible to accept or reject firmly one or the other of the two diagrams.

I must confess that my personal preference is for Kerr's Diagram.

Figure 14 shows a composite highly schematic drawing in which the optical data are shown in red, Kerr's 21 cm diagram in green and Weaver's in yellow. The circle of the Sun with a radius of 10 kiloparsec is shown in blue.

The most completely continuous feature of the Weaver diagram is the Sagittarius Arm, which, as we noted, has been traced optically over a considerable range by Becker and Fenkart, by Courtès *et al.* and by Lynga. Kerr sees this Arm as sections of two arms, one the traditional Sagittarius Arm, which, according to Kerr, bends inwards and becomes tangential at $l = 305°$, the other the Carina Arm of Kerr, which he draws starting at 5000 parsec from the Sun in the direction $l = 285°$. We note that the Kerr Carina Arm (and the Weaver overlapping section) go nicely together almost half-way around the Galaxy, starting from the point at $l = 285°$, 5000 parsec from the Sun, where they merge; the pitch angle is about 7°.

We naturally ask ourselves why there should be major differences between the interpretations by Kerr and by Weaver. In all researches on radio-spiral structure, we hunt first for effects that should be observed for directions where by chance we look tangentially along a spiral feature. In his Basel Symposium paper, Weaver showed with the aid of model-galaxy calculations how, from the (1, V), longitude vs radial velocity, diagram for regions in the galactic plane, we can locate these tangential directions. Figures 2 and 5 of Weaver's [9] Basel Symposium Paper illustrate the type of analysis used by him and Figure 4 of the same paper shows the diagram which represents the observations, north and south, according to Weaver. At present the observational material for southern galactic longitudes is notably incomplete. Weaver used a variety of sources in his preliminary analysis, some of dubious validity, notably so in the range $230° < l < 300°$. This could not be helped at the time. Kerr depended in part on unpublished material by himself and J. V. Hindman, but his data did not present a sufficiently tight net in galactic longitude and the latitude coverage was poor. The basic southern observational material will soon be supplemented with new data by Kerr and R. H. Harten, which they have obtained at Parkes during April and May of this year. The new material will have adequate latitude coverage, $-10° < b < +10°$.

Kerr observes in the third quadrant tangential features at $l = 284°$, 305° and 327°, whereas Weaver considers as established only one tangential feature, that at $l = 284°$. He ignores Kerr's feature at $l = 305°$, and attributes the edge at $l = 327°$, or thereabouts, to a deep inner Expanding Arm.

For the first quadrant, Kerr considers that he has observational evidence for three tangential directions, $l = 33°$, 50° and 75°. Weaver considers only $l = 50°$ as indicating a major tangential direction. He considers the others as originating from minor spurs and bifurcations. As a result the Perseus Arm and the Outer Arm are clearly marked in Weaver's diagram, but the Cygnus Arm is mostly lacking. Kerr on the other hand has the Cygnus Arm as a major feature, starting close to the Sun in a direction $l = 75°$, bending gradually inwards, and still traceable at $l = 20°$ on the far side of the galactic center. Off-hand it seems difficult to deny the presence of the major Cygnus feature, which, in the range $70° < l < 90°$, has been shown to exist optically in both gas and stars for distances from the Sun ranging between 500 and 4000 parsec, and which is also shown clearly in Burton's diagram.

The local spiral picture is still far from clear. In Weaver's diagram, the Cygnus-Orion Arm, observed optically, is mostly a stellar arm in a Local Spur that contains the Sun; this Spur branches off the Sagittarius Arm. Kerr's distribution of hydrogen within 1000 parsec of the Sun is confused and uncertain. He suggests that his Cygnus Arm connects directly with the Carina Arm and that the Orion feature is a minor Spur. In the final analysis, optical data will probably decide the run of spiral features within 2000 parsec of the Sun.

9. Conclusion

I apologize that I must conclude my Discourse on a note of uncertainty. Instead of being able to show a finished picture, with a 'Grand Design' in which most details fit nicely, I can do no better than present a confused and uncertain overall picture. I have tried to show that some major spiral features have been isolated, ranging in distance from the galactic center between 4 and 14 kiloparsec, and that the detailed 'anatomy' of several stretches of spiral arms is now known. But I must admit that we do not yet have available for future theoretical analysis the long-desired basic diagram of the galactic distribution of gas and young stars. We shall need at least another five to ten years to round out the total observational picture, a task in which we ask radio and optical astronomers to join us. And then we shall be able to give to Professor Lin the 'Grand Design' for which he has been begging since 1965!

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