PART V

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85. SUMMARY AND OUTLOOK

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1. Preamble

Our Symposium has truly been held in the spirit of IAU Commission 33. This Commission has traditionally provided the opportunity for optical and radio astronomers to meet with theorists interested in the dynamics of stellar systems. Our good relations with Commission 34 assure us that in our deliberations we shall not lose sight of the physical implications of our theoretical and observational developments. The past and present Presidents of Commission 33 are proud of the fact that they – and their Organizing Committees – took the initiative for holding this Symposium in Basel. We need not hide the fact that the plan to go to Basel came because many of us wished to honor Wilhelm Becker and his associates for the beautiful and basic researches they have done relating to the spiral structure of our Galaxy.

After Shapley's major discovery of the distant center of our Galaxy, with our sun assigned a position about 10 kpc from the center, the scene was set for the developments to follow. The outstanding new approaches came through the Oort-Lindblad theory of galactic rotation and Trumpler's proof for the presence of a general galactic absorption of the order of half a magnitude per kpc or greater in visual light for positions along the galactic equator. However, we seemed stymied in our attempts to study the spiral structure of our Galaxy in the 1930's and early 1940's, until in the late forties there came Baade and Mayall's propositions, based upon studies of M31, which showed that H II Regions and O to B2 stars are probably the best spiral tracers. Morgan took up Baade's challenge to determine accurate absolute magnitudes and absorption-corrected distances, and, between Christmas and the New Year of 1951, he presented the world with the Morgan-Sharpless-Osterbrock picture of the basic spiral structure near the sun. To Wilhelm Becker and his associates goes the credit for having put our local structure in order.

At the time when the first optical pictures began to appear, the discovery of the 21-cm line led Oort and his many associates – of whom I need only mention here Van de Hulst, Müller, Schmidt and Westerhout – to use the 21-cm profiles for probing the spiral structure of the Milky Way within reach of the Netherlands Radio Telescope at Dwingeloo; and Kerr, Hindman and others covered the parts of the Milky Way observable from Sydney, Australia.

Theory was slow in catching up with observations. Until half a decade ago, most of us in the field were of the opinion that the magnetic fields near the galactic plane were probably as strong as 20 or 30 μG, and fields of this stength would probably have proved sufficiently strong to hold the spiral arms together as magnetic tubes. This was an illusion – for it is now clear that the fields are no stronger than two or three

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microgauss at most. During all of the magnetic period basic research on the purely gravitational approach was being done by one person: Bertil Lindblad. His work on the theories of epicyclic orbits and on resonance phenomena laid the foundation for many current theoretical developments and Lindblad's name has been frequently mentioned in our deliberations. It is a pity that he was taken away from us rather early in life. He would have thoroughly enjoyed the present Symposium, and we ask his distinguished son, Per Olof, to bring our greetings to his mother. Theory took a new turn about five years ago, when Lin and Shu entered the field with the density wave theory. Whereas Lindblad concentrated on the orbits of stars and on waves in systems of stars, Lin placed the emphasis on density waves of stars and especially in the gaseous interstellar medium. The Lin-Shu theory is now in full bloom, but we must not fool ourselves and think that all is done except the mopping up. We have heard it repeatedly said at this Symposium that the Lin-Shu theory is only a first-order theory and that there is no guarantee that it will not require major modification before all is said and done. There is controversy aplenty even within the MIT-Harvard family and this is all to the good. Observers are following the theoretical debates with care and more and more shall we be able to present decisive observational data capable of proving or disproving the tenets of the theorists.

It is wonderful indeed to have had with us at this Symposium so many of the Prophets of the past. However, we must not overlook the danger that their formidable presence in our midst may serve to intimidate the young astronomers, physicists and mathematicians present who have fresh ideas on spiral structure problems. We must not let THE ESTABLISHMENT guide our future course. As far as I am concerned, my sympathy and attention have gone to the unconventional young astronomers with new approaches – and I for one will stick with them until their ideas are definitely shown to be wrong.

It is indeed a formidable task for me to try and present in one hour a summary of our deliberations of the past six busy days and also to discuss future trends. This Symposium has produced several ground-breaking papers, a large number of new and solid contributions to our knowledge and understanding of spiral structure, and there have been also some excellent peripheral papers. But we must admit that there were also a dozen or more poor and irrelevant papers, which took valuable time. In my survey and comments, I shall not deal with even the best of the peripheral papers – which include the fine papers by Vera Rubin and Ford, and by Ejnasto. I shall also not speak about those researches reported by our Russian friends which mostly did not deal specifically with spiral structure. I beg your forgiveness for not mentioning some papers fully deserving of comment, for I am only human and the time for preparation of my text was short – as was the time for presentation. The harvest is a rich one, but it had to be completed and stored before our departure from Basel!

2. Spiral Arms

We should ask ourselves first of all: *What is a spiral arm?* The beautiful photographs

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of typical spiral galaxies beyond our own – if there is such a thing as 'a typical spiral galaxy' – show us spiral features that are primarily gaseous in nature. The spiral arms that concern the optical and the radio astronomer and also the theorist in the field are most neatly demarcated as long connected streamers of hydrogen gas, many of which have shapes that resemble logarithmic spirals. The gas associated with a specific spiral feature is principally neutral atomic hydrogen, but inside these H I streamers there are generally many concentrations of more than average density, in which star formation has recently taken place and in which OB stars with ages of the order of 10^7 years and less are found. These OB stars come either alone or in OB associations or clusters, and near them we find most of the hydrogen ionized and observable as H II regions by both optical and radio methods. With reference to the Local Standard of Rest in our rotating Galaxy, these OB stars have not had time to have moved more than 50 to 100 parsec from their places of origin, which means that features at distances of 2 or 3 kiloparsec from the sun are observed by us within 1, or at most 2, degrees of their places of origin. At this Symposium we were reminded of many facts that we might otherwise overlook. For example, Weaver remarked that the temperature of the H I in spiral arms is probably close to 100 K, whereas in the interarm regions – with gas densities of the order of one-tenth that in the arms – we may have average temperatures of 1000 K and more; and we always bear in mind that the H II regions have temperatures of the order of 10000 K.

Apart from the OB stars, alone or in associations and clusters, the long-period cepheids and possibly also the WR stars and the early Be stars, are about the only decent spiral tracers. As McCuskey made clear in his thorough paper, the common stars are generally too old to be of much help. They may define 'fossil' spiral features, but most of the common stars have moved too far away from their places of origin to suit us. Moreover, the original regions of their births will probably be no longer in troughs of spiral potential. By now some of these positions of origin are likely to be in inter-arm regions!

To provide a basis for the beginning of a theory for the spiral structure of our Galaxy the optical and radio observers are asked to provide answers to two difficult varieties of fundamental questions. These are: (1) what are the principal characteristics of a spiral feature, be it a section of a major spiral arm, a connecting link, or one of the wisps or feathers that we observe emanating from spiral arms; (2) what appears to be the best pattern of overall spiral structure applicable to our Galaxy? The optical astronomer who studies our Galaxy is mostly limited to providing answers to the first question, whereas the giving of answers to questions relating to overall structure and pattern is primarily the province of the radio astronomer. The optical astronomer helps to provide guidelines for answers to questions relating to patterns and to overall structure mostly through the study of galaxies beyond our own stellar system which show spiral features of one sort or another. The theorist blends it all, constantly showing impatience at the inefficiency of optical and radio astronomers alike, who struggle with their basic data and who, for the taste of the theorist, are not providing fast enough simple and comprehensive answers to the basic questions which the theo-

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rists wish to have disposed of once and for all. Most of the theorists at our Symposium were applied mathematicians with commendable profound interests in gas and stellar dynamics. I only wish that we might have included a bigger representation of physicists and astrophysicists, for the great problems of our Galaxy are basically problems of physics.

3. Spiral Galaxies of the Local Group and Beyond

Our Symposium began with two fine presentations; one by Oort, the other by Morgan, who both stressed the terrific importance of studies of galaxies of the Local Group and beyond that show spiral features.

Morgan showed us some beautiful Hα photographs taken mostly by Garrison with the Yerkes 40-inch Reflector fitted with a reducing camera of Meinel design and appropriate interference filters. Many comparable Hα photographs were shown, by Courtès, Cruvellier, the Georgelins and Monnet, by Mme Pronik and by Khachikian. I understand that more could have been shown – by Bertola for example – if there had been time. It has been wonderful to have seen these excellent samples of photography for some of our prized neighbors, M31, M33, M51, M83, M101, NGC 628, NGC 1232, NGC 4254, NGC 4643, NGC 6943, and others. To supplement the material presented at our Symposium, we now have Hodge's fine photographs published earlier this year (*Astrophys. J. Suppl.* **18**, 73, 1969) and there is the promise of an extensive study of Hα photographs to be published by Kristian and others at Mount Wilson and Palomar Observatories.

While it is essential that we should stress in all theories of spiral structure that the prevailing type of structure shows two principal arms, we should bear constantly in mind that there are many exceptions to this rule. Oort stressed in his Opening Address that in half of the spiral galaxies we have evidence for more than two arms. Often we find features between the arms, or secondary branches, or links between arms, or feathers and bifurcations in major arms, some so strong that it may be difficult to follow the basic pattern. Morgan and Vorontsov-Velyaminov considered the problems in their addresses. Vorontsov-Velyaminov considers the lack of agreement between the available spiral plots of our Galaxy a very serious matter and he presented evidence to show that there may be no traceable spiral structure at distances greater than 10 kpc from the center. Bortchkhadze's paper drew renewed attention to the presence of several separate spiral arms in the multiple-arm system NGC 1232. He finds also as many as nine sections of arms in one quadrant of NGC 5247. Rudnicki added NGC 3486 to the list of notable multiple arm systems. It is worth stressing that multiple arms prevail in the outer parts of spiral galaxies, but that close to the nucleus two distinct arms are generally shown.

Many of the participants to the Symposium were bewildered by the variety of spiral structures and vaguely spiral-like structures for the neighbor galaxies for which photographs were shown. It was reassuring to hear de Vaucouleurs state unequivocally that all of these can be sorted according to about 10 classes, with *openness* of

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spiral features, the presence of a *ring* and of a *bar* as the first items to be judged for classification.

The difficulties of classification by appearance alone were stressed in Morgan's address. He showed how relatively straightforward it is to classify irregular and spiral galaxies by integrated spectra ranging from A to K for Irr to Sc to Sb to Sa to S0, with the giant ellipticals naturally following after that.

To supplement the plentiful Hα photographs, we need now extensive radial velocity studies of the types reported by Courtès, Cruvellier, the Georgelins and Monnet and by Mrs. Simkin. And we are of course all waiting anxiously for the results of the promised high resolution 21-cm surveys of galaxies; Baldwin promised results with resolutions of the order of 1 min of arc, or better! It is likely that from studies of nearby galaxies with spiral features, we shall be able to derive in the near future firm data on the relative widths of the spiral arms outlined in H II and compare these with the widths of the H I arms. This observational information is urgently needed for the study of *where* inside a spiral feature star formation has most likely taken place. Is it near the inner or near the outer rim of a spiral arm, or does the backbone of star formation run down the middle of the H I arm? How wide is the band of star formation and how does its width compare to the width of the H I feature? Is star formation limited – as I have long thought it is – to regions of abnormally high gas density, say 10 times the average for the arm as a whole?

The excellent paper by Beverly Lynds taught us much that is new about the distribution of dust in spiral galaxies. In the first phase of her work she has studied the distribution of dust in 17 Sc galaxies, all of them seen practically face-on. Her sketches confirm and extend our earlier knowledge on the subject. The 100-inch and 200-inch Reflector photographs, made available to her by Sandage, confirm Sandage's and Baade's assertions that dust lanes appear first close to the nucleus, to be followed by luminous spiral arms, with the dust arms in the inner parts at the insides of the luminous arms. Lynds finds that young stars and dust go together and that the brightest H II regions are generally found at the edges of dark lanes. Dark 'feathers' are often traced across a luminous arm and these must be considered a common feature, according to Lynds. An interesting result of her studies is that in several galaxies, notably in NGC 628, the luminous outer arms are 'sandwiched' between obscuration on either side. The continuation and extension of this work is obviously important and urgent.

4. Gravitational Theory

We are fortunate indeed that the theorists attended our Symposium in force. The theoretical keynote address was brilliantly delivered by Contopoulos, who gave us a full introduction to the gravitational approaches to the dynamics of spiral structure. At the start he intimated with his customary firmness that discussions of possible magnetic effects would be taboo. And so they were! We had to wait until the end of our third day, when I took it upon myself to refer to the fact that not so long ago spiral arms were tentatively explained as being held together by magnetic forces.

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There were some mighty attractive features to the theories of a decade back in which spiral arms were viewed as magnetically bound tubes of ionized gas. Unfortunately the observed galactic magnetic fields fell short in strength by an order of magnitude compared to the required fields, but no one should overlook the celestial message reaching us through maps of optical polarization, which show the most orderly alignment when one observes across a galactic spiral feature. The magnificent work of the MIT group loosely headed by C. C. Lin has made the pendulum of interpretation swing toward Bertil Lindblad's gravitational approach, and this is wonderful indeed. But I look forward to the next decade in which the pendulum may favor a middle course with shared emphasis on gravitational and magnetic effects. I hope that the members of our Symposium who will attend the Symposium next week in the Crimea will remind the physicists present there that the astronomers and applied mathematicians are urgently in need of consultants in physics to help them resolve some of the big problems of spiral structure.

At the start of his remarks, Contopoulos stressed that the basic contribution of Lin and Shu was that they apparently removed the dilemma of the winding up of spiral arms. Lin, Shu and Yuan introduced and developed the concept of a spiral wave pattern of potential, moving through our Galaxy at a rate of rotation less than that given by the Oort-Lindblad rotation. All workers in the field give deserved great credit to Bertil Lindblad's concept of a gravitational theory which he began to develop more than a quarter of a century ago. The spiral arms are not viewed as permanent entities with some stars and some atoms and nebulae belonging to a spiral feature, others not, but rather do we see spiral arms now as loci of star concentration coinciding with spiral-shaped potential troughs. The stars and the gas move through the spiral arms, but on the average they prefer to linger in the arms and speed through the relatively thin inter-arm voids. Once a spiral system of two trailing arms has been established, the system will according to Lin and Shu apparently be a gravitationally self-perpetuating one. By the proper selection of the rate of rotation for the spiral potential field, with a value for the pattern speed $\Omega_p = 13.5$ km s^{-1} kpc^{-1} now favored by Lin, Shu and Yuan, a tightly wound near-circular system of two trailing spiral arms is produced, which shows many features known to exist in our own and neighboring galaxies.

As expected, grave doubts were expressed about some of the theoretical interpretations and different approaches were suggested. Contopoulos referred to these new ideas, many of them quite different from the Lin-Shu-Yuan approach. Later in the program the relevant papers were presented and we heard about Fujimoto's hydrodynamical approach, about Kalnajs's work on very open spiral systems with pattern speeds very much greater than those of Lin and Yuan, about Toomre's modification of Lin's theory, in which the waves show inward motions, and about Hunter's work on large-scale oscillations of galaxies. It is useful to have these approaches developed further since they may come in very handy if and when observers obtain evidence for axisymmetrical radial inflow or outflow of gas in our Galaxy. As of now, the observed humps in the basic observed curves giving circular velocity versus distance from the galactic center, one applicable to the first quadrant of galactic longi-

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tude, the other to the fourth quadrant, can be best understood in terms of the theoretical spiral structures and fields developed by Lin and by Yuan. But we should not forget that 10 years ago many of us looked with favor upon Kerr's suggestion of a radial outflow of gas at the sun's position of 7 or more km per sec. Hunter's modes would help understand such results.

The basic kinematical problem was discussed in a thorough paper by Blaauw, who finds that the Local Standard of Rest – as defined by objects associated with the halo and the nucleus of our Galaxy – has velocity components of the order of 5 to 10 km s^{-1} with respect to the gas and the youngest stars. He stressed in his presentation that the gas in our vicinity is surprisingly quiescent, but that the youngest stars move in turbulent fashion in the solar neighborhood. He noted that any observer located in the Perseus Arm would have difficulties in sorting out the kinematics of motions of stars within a few hundred parsec of the sun.

Throughout the theoretical presentations, the limitations of Lin's first-order theory were stressed. First-order theory fails near the Lindblad resonance points, especially near the critical distance where rotational and epicyclic frequency become commensurable. Four-arm spirals then become a possibility! Lin has concluded that spiral-shaped gravitational waves of potential cannot exist within the inner Lindblad resonance circle.

On the fourth day of our Symposium Lin and Yuan spoke about recent developments in the density wave theory. The observational astronomer is especially pleased to learn about the interest our theoretical colleagues are showing in observations, and it is a source of regret to the observers, optical and radio alike, that we cannot agree as yet on the full outlines of spiral structure for our Galaxy. Give us a few more years, and we shall be able to tell you all right! Lin and Yuan have fitted their theoretical pattern primarily to the Kerr diagram of spiral structure. The theoretical pattern will have to be revised if the spiral diagram of Weaver proves to be the more acceptable one. In all observed radio diagrams the Orion Feature looks increasingly more like a spur than a major arm. The most spectacular optical feature, the Carina Feature, remains a source of embarrassment to radio astronomers and theoreticians alike!

Yuan has undertaken the time-consuming, but very useful, task of calculating 21-cm profiles on the basis of his modified Lin model. This approach is to be highly recommended for the future, for it is only in this manner that we shall be able to decide in the end which theoretical model fits best with our observations.

The paper by Yuan gave us some useful basic tests of the Lin-Shu theory. A further test – to which we should refer at this time – is that provided by the analysis of Burton and Shane. Their first observational analysis, announced 3 years ago, gave evidence already for streaming effects very much in line with those to be expected from the Lin-Shu density wave theory.

Lin made some very interesting suggestions regarding the outer-arm structure. Multiple arm systems become quite possible in the outer parts, but the spiral arms will probably not extend beyond the place where the pattern speed equals the rate set by

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normal galactic rotation. As a matter of fact, he suggests that the pattern speeds of external galaxies can be found in principle by noting the distance from the center of the galaxy at which the spiral arms seem to end. There is considerable doubt about the fate of density waves in the outermost parts of galaxies.

5. Origins of Spiral Patterns

The Lin-Shu-Yuan theory of spiral structure suggests how, in all likelihood, the spiral potential field, once formed, may be automatically maintained, but the authors have not yet suggested a well-developed mechanism for the original formation of the basic spiral potential field. Toward the end of the Symposium, Lin made a suggestion, which was developed as a result of discussions with Shu and Toomre. Trailing spiral arms, co-rotating with the general mass motion, are produced through the stretching of irregularities in the outer parts of a galaxy because of effects caused by differential rotation. Resonance produces a situation in which only a two-armed structure will prevail when the disturbances propagate inwards as a group of waves. These waves should extract their energy from the basic rotation of the galaxy, as sketched by Lynden-Bell and others.

Most of us present at the Basel Symposium felt quite pessimistic about the present status of our knowledge *why* it is that spiral structure seems to prevail on such a wide scale in galaxies. The exception was Oort, who, in his Opening Address said: "Indeed, any mechanism of formation of a rotating galaxy is likely to produce a system with large-scale initial asymmetry in the plane of rotation, which will almost automatically develop into a two-armed spiral structure." Let us hope Oort is right. On Saturday afternoon we were exposed to a number of widely different theoretical approaches by Toomre, Lynden-Bell, Shu, and Kalnajs, and on Monday morning we heard further on the subject from Vandervoort, and indirectly from Marochnik.

Toomre put some of the possible blame for starting our Galaxy's spiral structure on a close passage of the Large Magellanic Cloud to the plane of our Galaxy. But on further consideration he was not very certain of this approach, for he 'shuddered' at the resulting violent effects that would be produced if this were to happen, effects so turbulent and disruptive in character that they would hardly help to give birth to the majestic and all-pervading spiral potential field of Lin.

Lynden-Bell sketched an approach in which a ring would form at the distance from the center of the galaxy at which the rotation period would be in resonance with the pattern speed of the density wave. If the star density decreases outward, then there would be more stars pushing just inside of the ring, stars with greater rotational speed, than there would be stars holding back the ring – laggards Lynden-Bell called them – at distances just outside. This mechanism would provide the energy to start a density wave on its track outward from the inner ring. Thus we may expect a trailing spiral pattern outside the resonance ring. The main energy of the spiral pattern is thus derived from galactic rotation. Lynden-Bell pointed out that the Lin-Shu theory in its present form does not consider the transfer of momentum from one part of a galaxy

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to another, something which he considers basic for our understanding of the starting and maintaining of a spiral pattern of potential.

Shu was quite pessimistic. He pointed out that resonances primarily affect stars and *not* the interstellar gas, the atoms of which are constantly interacting. This conclusion applies especially to the Lindblad resonances, in which we deal with stars moving in neat and relatively constant epicyclic orbits. Stars do not interact violently in short times. Shu expressed the opinion that resonances have a tendency to hinder spirality rather than help it and he sees no evidence for instabilities general enough and sufficiently powerful to start a natural disturbance in the interstellar gas on the scale required by the prevalence of spiral structure in galaxies.

Vandervoort showed that spiral-like streamers of finite amplitude will occur naturally if a thin gaseous rotating disk – think of Population I – rotates in the midst of a gravitational field produced by a not-so-flat disk and a halo of old stars – think of Population II. Inside the possibly very thin first disk spiral features will naturally develop. They are like thin spiral frosting on a very large cake!

To initiate a spiral potential field, one obviously requires some feature that is non-axisymmetrical in character. Following Freeman's comprehensive and elegant treatment of Barred Spirals, Toomre advanced the suggestion that we may have overlooked the most promising spiral feature of all: *the Bar*. This suggestion is very much in line with that made on several past occasions by Pikel'ner. Toomre noted that Freeman and de Vaucouleurs had stressed the smoothness of the transition from extreme barred spirals, to spiral systems with minor bars, to true spiral systems – if there are such things. Thin gaseous disks in rotation are eager to be excited and any disturbance will almost naturally produce a spiral potential field. The Lin-Shu theory, or one of its modifications, probably provides the machinery for keeping the two-arm spiral potential field intact once it is formed.

One approach to the formation of a Bar comes from Kalnajs's work. He showed that flat-disk galaxies, which are stabilized by random motions to withstand violent axisymmetric instabilities, are still capable of gradual evolution. In the inner part of a rotating galaxy some sort of collapse may take place, which would result in a density wave which would in turn produce a feature looking very much like a bar with two little trailing streams. Angular momentum and energy must be disposed of and these may be transmitted to the outer parts. Kalnajs requests observers to provide him with data on the velocity fields for the whole of a galaxy, not just for sections of arms, since he wishes to know the observed deviations from circular motion and fit these into his theory.

Our theorists should be encouraged to continue their search for basic mechanisms to produce spiral potential fields on a large scale in rotating gaseous systems – and barred spirals should by all means be included in all such studies. The observational astronomers interested in studies of galaxies should make increased efforts to study the structural and kinematic properties of barred spirals in the expectation that the dynamicists will find much use for the results derived from such observational studies. The properties of cosmic dust in bars should be studied. During our discussions, there

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was brief mention of some hydrodynamical laboratory experiments that might throw further light on problems of the formation and stability of spiral features. This is an approach that deserves to be encouraged.

Prendergast and Miller presented the Symposium with the results – in a film – of some spectacular numerical experiments. The results of similar work by Hohl were presented by Toomre. It is now practicable to study the evolution of star systems with tens or hundreds of thousand of stars, and follow their patterns of motion and distribution under the inverse square law of attraction. In Prendergast and Miller's experiment clouds of gas are gradually turned into stars, the rate of star formation being held proportional to the square of the density. In the film we saw trailing spirals, bars and rings, forming and disintegrating before our eyes. Density wave effects were especially noticeable when about 25% of the galaxy was still in gaseous form. These striking patterns were found in the gas rather than in the star pictures.

Miller commented that these experiments are not done to provide at great expense spectacular films, but that we now have a tool for actually experimenting with spiral galaxies and studying problems of internal structure, motion, stability, and evolution.

In judging these films one should bear in mind that they show basically information on the motions of mass points or mass units in a self-perpetuating gravitational field. Care must be exercised when direct comparisons are made with photographs of spiral galaxies – which show basically brightness distributions. We should, furthermore, bear in mind that the underlying gravitational potential field is mostly controlled by the stars, rather than by the gas. The gaseous spiral patterns must be viewed against this background of a distribution of stellar masses.

So much for galaxies other than our own, and for pure theory. Now let us turn to our Galaxy and discuss its observed radio and optical properties, bearing in mind that this is a Symposium on The Spiral Structure of *our* Galaxy!

6. Radio Spiral Structure of Our Galaxy

The *Baseler Nachrichten* referred to our Symposium as the first international gathering ever of optical astronomers, of experts in galactic dynamics, and of the world's greatest radio *astrologers*. I viewed with pleasure the horoscopes of galactic spirality, which our distinguished radio colleagues had prepared for the occasion. Some of these were skillfully animated in the best of the early Mickey Mouse tradition. It seems as though Mezger, Kerr, Westerhout and Weaver are doing as well by our Galaxy as Kepler did by Wallenstein!

The major radio astronomical papers at our Symposium were those of Mezger and others at NRAO, MIT and the CSIRO on distribution of H II regions, and of Kerr, Weaver, Westerhout, Varsavsky and others on H I features of our Galaxy. This Symposium will become known as the occasion on which major steps forward were made in our knowledge of the radio astronomical evidence for spiral structure in our Galaxy.

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Mezger's presentation of the H II data by himself, Wilson, Gardner and Milne showed that we now have information on the radial velocities of H II regions for practically all of our Galaxy. The interpretation of these data is not a simple matter, since there still is much confusion about near and far distances corresponding to radial velocities for H II Regions observed within the circle with a radius of 10 kpc centered upon the center of our Galaxy. Morgan commented that many ambiguities can be resolved in the years to come by careful optical work of the variety that is now being done for the transparent sections of the Milky Way in Carina. The H109-α velocities, when interpreted by themselves alone and as best we can, do not yield spiral patterns that make sense. But these data should be invaluable when sorted in conjunction with H I-21 cm profiles and with optical data. All of us who work on the spiral structure of our Galaxy will want to have the NRAO-CSIRO-MIT Catalogue within easy reach at all times.

Two outstanding facts are to be noted. The first is that there is a striking apparent total absence of H II regions within a central circle with a radius of 4 kpc. The second item to be recorded is that there exists a class of giant H II regions, all with flux densities equal to 4 times that of the Orion Nebula or greater, which show their highest concentration within the band between 4 and 6 kpc from the galactic center. The bulk of the H II regions peaks at distances between 4 and 8 kpc from the center, which is in marked contrast to the H I distribution, which peaks between 8 and 15 kpc from the galactic center.

Conflicting H I results were reported by Kerr and by Weaver.

Kerr presented the basic picture reproduced in his 1969 *Annual Review* article, one that is based on the work of himself, Hindman, Westerhout and Henderson. The Perseus Arm, the Cygnus-Carina Arm (with the sun at the inside and the Orion Spur emanating from it), the Sagittarius Arm and the Norma-Scutum Arm are basic features of Kerr's patterns of spiral structure. These arms appear to be near-circular and tightly wound with pitch angles of the order of 5° to 7°. Kerr notes that the H II Regions are generally found close to the ridges of greatest H I intensity. In the outer parts of our Galaxy, the contrast between arm and interarm gas density runs as high as 10 to 1, probably less in the central regions of our Galaxy. The dipping of the spiral arms over long stretches below and above the galactic plane is quite striking, features that stand out wholly apart from possible oval distortions and the bending of the galactic plane in the outer parts.

This may be a good place to mention in passing a very important result announced by Oort, who spoke of the work of Miss Kepner. She finds marked concentrations of H I at heights above or below the plane as great as 1 to 3 kpc. The observed velocities show this hydrogen gas to be clearly related to some of the major spiral features, like the Perseus Arm. It must have been expelled with terrific speeds – possibly explosive speeds – from its parent spiral arm to have reached such heights. Similar results were announced by Weaver from his northern survey.

From the observations made at Hat Creek in California, supplemented by the Kerr and Hindman data for the southern Milky Way, Weaver derives a spiral pattern

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for our Galaxy very different from that favored by Kerr. His pitch angles for the arms are of the order of 12° to 14° and the principal arms that are shown are the Perseus and Sagittarius Arms. The sun is in the Orion Spur – which is not a major feature. The Carina Arm is almost wholly incorporated in the great Sagittarius Arm, and a residual feature becomes a very minor local loop of the H I pattern. The Norma-Scutum Arm is not clearly shown as in other diagrams. Weaver pays much attention in his analysis to the directions from the sun in which the velocity vs. galactic longitude diagrams exhibit loops which show that for that direction one looks tangentially along a major spiral arm. One such loop is at galactic longitude 284° (in Carina), the other at longitude 50° approximately.

Every effort must be made to find with minimum delay the reasons for the differences between the Kerr and Weaver patterns. The procedures used by Kerr have been described in detail, but Weaver's results are so recent that we have only a general notion about his procedures of analysis. Weaver stressed that his results are still highly provisional. Both analyses suffer from relative incompleteness of data in the southern hemisphere, where there are many gaps in the coverage of profiles and where there is a need for tighter latitude coverage. Thus far Weaver has admittedly not paid sufficient attention to integrated intensities of his profiles and he has not used effectively the distribution in latitude for disentangling the near and far H I in directions for which the radial velocity resolution is poor. There has been no time to call in radio H109-α velocities and data on optical H II regions to adjust his 21-cm results. In a way we are stymied until Weaver and Kerr get together and arrive either at more nearly compatible spiral patterns, or until one shows that the other's pattern has serious deficiencies. It is most desirable that the available data be published in full – and, as I understand it, this is being done. Careful independent analysis of the basic material by others seems desirable, but this is not to be undertaken lightly. Perhaps such analysis should wait until the southern profiles catch up in quality and coverage with the northern ones.

Varsavsky reported on the progress of the work now under way in Argentina. He confirms many of the features shown by Kerr. The low-latitude work of Miss Garzoli should contribute especially to our knowledge in the critical longitude range 270° to 310°.

We should not fail to refer to the beautiful results shown in the form of films by Westerhout and by Weaver. Westerhout concluded from his observations with the NRAO 300-foot antenna that H I spiral arms are really conglomerations of H I clouds, with little background in between, that the H I density between arms is often quite low, that the Orion Arm or Spur is far less impressive than the Perseus Arm, and that we have now good evidence for a Distant Arm, well beyond the Perseus Arm.

Burton and Shane presented some new results for the inner arm structure. Their analysis relates beautifully the expanding 4 kpc Arm to inner and outer arms of which sections are viewed on both sides of 56° galactic longitude. The ratio of arm to inter-arm density seems to be different here from the outer parts, with 1 to 3 being a favored average for interior structures. Their values for the pitch angles of the arms are 8° for the inside features, 5° for the outside ones.

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To summarize: We now have information on spiral features in the range of distance from 4 to 5 kpc from the center to 14 or 15 kpc, but the present controversies will have to be resolved before we can say that we have a spiral pattern that is generally agreed upon as the more or less overlying pattern for our Galaxy. Observers are not yet ready to present the theorists with the 'grand design' of C. C. Lin's dreams.

7. Optical Spiral Structure of Our Galaxy

The discussion of optical studies relating to the spiral structure of our Galaxy opened with a paper by McCuskey on the stellar component of our Galaxy.

McCuskey concludes that (1) the OB^+ and OB^0 stars, WR stars, early Be stars, O Associations, some S and N (carbon) stars, are linked to spiral structure; (2) the B5 and B8 to A3 main sequence stars, classical cepheids of longest periods, early M giants (including variable stars) are possibly loosely associated; (3) the remaining main sequence stars to F8, the yellow-red giants, the M giants later than M5, as well as the remaining S and N stars, are not related to spiral structure.

Next comes a comprehensive paper by two of our hosts, Becker and Fenkart. This paper extends the results given half a decade ago by Becker, Fenkart and Steinlin and it confirms the existence of three optical spiral features, the Perseus, the Orion and the Sagittarius Arms, while adding a fourth, the Norma-Scutum Arm. Fenkart pointed out that the possible connection between the Cygnus and Carina Arms, which I have advocated in the past in the longitude section 280–300°, is erroneous since there is a void of 1.5 kpc between the sun and Carina in which there are no H II regions and OB clusters in association. The Becker-Fenkart spiral pattern fits well into the overall spiral structure in the outer parts of NGC 1232.

Courtès, Cruvellier, the Georgelins and Monnet presented their beautiful work on optical H II regions. With the aid of radial velocities and optical distances for exciting stars, they have been able to outline an optical pattern, which includes the Perseus, Orion, Sagittarius and Norma-Scutum Arms. The French astronomers conclude that the OB stars, the long-period cepheids and the H II regions all have precisely the same velocity characteristics. We note that the pitch angles of the spiral arms traced by Courtès *et al.* are about 20°. The Swiss and the French astronomers place the sun at the inside of the Orion Arm.

I am happy to let these results stand unchallenged, and yet I feel that the last word may not yet have been said on this subject. Even with the best efforts, optical astronomy is by its very nature interstellar-absorption limited and, while we may for some longitudes reach to 6 or 8 kpc distance from the sun, we shall more likely on the average be limited to distances half that great. The radio astronomer is not limited in his analysis by absorption. Once we know the kinematics of our Galaxy, we can analyse our 21-cm profiles and H109-α velocities and examine the overall pattern of structure. The optical astronomers are all agreed where are the principal concentrations in spiral arms visible from the sun's position in our Galaxy. The connecting of these clumps and sections of spiral arms into an overall spiral pattern should come from a blending

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of optical and radio information. I hope to see the day when we shall be able to hand to the theoretical astrophysicists and applied mathematicians a trustworthy model of spiral distribution and kinematics ready for comprehensive theoretical analysis; we are not yet at this goal.

Tammann presented a paper on the galactic distribution of long-period cepheids, those with ages of the order of 3×10^7 years and less, periods 11 days and greater. Color observations in UBV alone can yield good absorptions and distances for stars that are far more distant than the faintest OB stars within reach. The discovery rate of these cepheids must be stepped up, for here is an area in which optical astronomy stands to make major new contributions. Tammann's paper deserves careful attention.

Increasing emphasis is being given to detailed optical studies of sections of the Milky Way in which we are clearly observing specific spiral features. Mrs. Dickel, jointly with Wendker and Bieritz, has made a special study of the nebulosities in the Cygnus X region, longitudes 70° to 90°. Not only have they found structural patterns which appear to be related to the local magnetic field, but they have obtained new and interesting data on the geometry and internal structure of the spiral feature. The paper by Dickel *et al.* sets a fine pattern for future research.

During the early days of the study of spiral structure by optical means the Carina-Centaurus section, between longitudes 270° and 300°, did not receive the attention it deserved. This is no longer so. At our Symposium there were five papers devoted to this section and those immediately preceding and following it. The days of Carina neglect are past.

Optical data, supported by radio evidence from Argentina and Australia, show that the Carina feature is sharply bounded at galactic longitude 283° to 285° and less sharply at about 295° to 300°. The lower longitude limit is shown beautifully by Graham's work which proves the presence of OB giants and supergiants along the sharp edge over distances between 2 and 8 kpc from the sun. Velghe and Denoyelle have studied the thickly absorbed section with longitudes 260° to 283°. The absorption is very great in spots but, in spite of this, the absence of OB giants and supergiants between longitudes 265° and 275° seems definite. The absence of radio continuum found at these longitudes gives further proof that between 283° and 285° we are truly observing along an edge of a major spiral feature. Lyngå has shown that the absorption at the far-longitude edge is not exceptionally great. He finds a total absorption A_V of about 2 magnitudes at $l^{II} = 298°$ applicable to a distance of 3 kpc and nothing much beyond to a distance of 6 kpc. Obviously the inside of the arm is not very rich in cosmic dust.

Because of these low absorptions it becomes possible to outline the detailed internal structure of the Carina Spiral Feature. Together with my associates Alice Hine and Ellis Miller, making use of the standard UBV sequences established jointly with Priscilla Bok, we have been able to study the 'tree-rings' for two sections through the Carina spiral feature, one at 2 kpc, the other at 4 kpc from the sun. Each cross-cut in the section between longitudes 283° and 295° is rich in OB stars, H II regions and cepheids. These are spread in depth. E.g. Seggewiss, has determined the distance to one OB concentration, which is about 2 kpc. The point to stress is that the ridge of

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H II concentrations and of young OB clusters and associations is narrow compared to the broad band of H I.

The width of the ridge of H II features is about 800 pc, that of the H I spiral arm 1500 pc. For the Carina Spiral Feature we have now definitely located the position of the ridge of young stars and ionized hydrogen within the broad spiral feature. It should be possible to do in the future much detailed structural analysis on the internal affairs of spiral arms. A purely theoretical paper by Roberts bears directly upon these problems. On the basis of the Lin-Shu density-wave theory, he has calculated where, inside a broad H I feature, the strongest gas concentration will occur. He visualizes the formation of a shock wave, which will remain stationary and coincident with the background spiral arm, and which will lead to the piling up of much gas along a narrow ridge within the broad H I feature. Near the ridge dense gas clouds will be naturally condensed to such an extent that star formation takes place. Roberts' Two-Arm-Spiral Shock-Pattern provides good check lines of positions where, according to theory, observers should find bands of star formation. It is most encouraging that Roberts' work suggests the formation of narrow ridges of star formation within broad neutral hydrogen features which is precisely what we observe in the Carina-Centaurus Feature.

One result of the studies of the Carina-Centaurus Section by both optical and radio techniques is that the major spiral features are here found concentrated at galactic latitudes $-1°$ to $-3°$. At 5 kpc from the sun the principal concentrations lie 200–300 parsecs below the standard reference flat galactic plane.

The listing of OB stars at Warner and Swasey Observatory by Stephenson and Sanduleak promises to yield a wealth of new material for future studies of the southern Milky Way. Our Symposium voiced strong support for the suggestion that funds be made available for the preparation of first-class identification charts to show the positions of the southern OB stars.

I should mention that a potentially new spiral tracer was added to our lists. Mills gave evidence to show that pulsars are found mostly in or close to the galactic plane and they seem to show a remarkable preference for being located in spiral arms!

8. Influence of Magnetic Fields

I shall be brief in my comments on the final morning session. Woltjer's opening remarks set the tone for the analyses of magnetic fields and their effects. The average large-scale magnetic field can be determined by now quite well from Faraday rotation observations, since values of n_e (of the order of 0.05 per cm^3) from pulsar data are now available and these appear to be quite precise. The fields are of the order of a few microgauss, probably no greater than 3 microgauss. Such magnetic fields are so weak that they will largely be dragged along with the gas and, if the gas goes through a density wave, the field may be expected to be bent accordingly. From Woltjer's paper and the ones that followed it, it became clear that magnetic fields do not contribute effectively to the maintenance of spiral structure. However, they do have some signi-

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ficant side-effects. Their influence on the rolling of spiral arms may become a very active topic for future observational and theoretical analysis. And we may expect strong magnetic fields in condensing gas clouds.

Mathewson's discovery of a localized helical field complicates all analyses of polarization data. Fortunately optical polarization measurements are now becoming available in abundance, and it should be possible to disentangle effects caused by the local field from those produced by spiral features. Polarization data were especially needed for the long-neglected southern Milky Way. Verschuur reported that Mathewson has ready for publication a catalog with several thousand measurements, and Klare and Neckel showed their results for over 1400 stars, all of them along the southern Milky Way. These data should be exceedingly informative, especially when combined with good data on magnitudes, colors and absolute magnitudes of all stars with polarization measurements. Let us hope that the helical field may not unduly complicate the analysis and interpretation!

The final morning session was a very rich one. We had Spiegel's presentation of the conditions inside the 4 kpc arm. He visualizes a system of hydromagnetic flow acting upon gas emitted by the galactic nucleus and thrown out from the galactic nucleus into the central region, where he assumes the streaming to be guided by a magnetic field. At about 4 kpc from the center, this gas is ejected from the galactic plane, some to the north, the rest to the south. Supposedly, most of it returns in graceful arcs toward the galactic nucleus.

The final paper of our marathon series was one by Paris Pişmiş. She spoke about her series of papers on the Origin of Spiral Structure published in Tonantzintla and Tacubaya Bulletins Nos. 19, 21, 23, and 30. Time for presentation was short – so we were all asked to read these papers with care. Which is one reason why I shall now sit down and go home!

Notes Added December 1, 1969:

The readers of the Basel-Symposium Volume should be aware of two papers about to appear in print, which were not available to us at Basel.

(1) At the Symposium much indirect attention was given to barred spirals as a possible intermediate stage in the formation of normal spiral galaxies. Following the Basel Symposium, Margaret Burbidge prepared a paper summarizing the published observational data. This paper will be published in the January/February issue of *Comments on Astrophysics and Space Physics*. She describes a variety of models of barred spirals, in which the morphological trend is from subclass *c* toward subclass *a*, and in which barred spirals will naturally tend to evolve into normal spirals. More observational material on absorption lines in barred spirals is urgently required. Some years ago A. D. Code reported, at a Colloquium held at Steward Observatory, large velocity gradients exhibited by absorption features in bars, but no published data are available.

(2) The December, 1969, issue of *Sky and Telescope* contains an article by H. C. Arp: 'On the Origin of Arms in Spiral Galaxies'. Arp explores in this article the suggestion

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that spiral arms represent the tracks of material ejected from galaxies. This possibility was not discussed at Basel and deserves careful further attention by theoretical astrophysicists, optical and radio astronomers. The approach represents truly an "explosive theory for the origins of spiral arms" quite different from the theoretical approach of the Lin-Shu theory of gravitational density waves.

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