SECTION II.5

SPIRAL STRUCTURE

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F.J. Kerr (centre) catching up with I.F. Mirabel's research over pre-dinner drinks at Lauswolt. Left: C.A. Norman and B.F. Burke, right: L.A. Higgs LZ

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SPIRAL STRUCTURE OF THE MILKY WAY AND EXTERNAL GALAXIES

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ABSTRACT

The spiral structure of the Milky Way galaxy has always been somewhat elusive because of our internal vantage point. This review will present methods and data for determining the overall pattern, and will summarize various models that have been proposed. Observations of spirals in external galaxies will also be discussed, because they can provide insight into the spiral structure of the Milky Way.

1. OBSERVATIONS OF SPIRAL STRUCTURE IN OUR GALAXY

1.1. Spectrophotometric distances

There are four common methods for determining the distributions of stars and gas. The first method, plotting known stellar distances, is the most direct way to determine the structure of our Galaxy. The only disadvantages of this method are that distances are usually accurate to only ∿10%, which leads to large uncertainties for distant stars, and that there is a relatively small number of objects to which this method may be applied. Morgan, Sharpless and Osterbrock (1952) first found that OB associations outlined spiral arms in the Milky Way. Open clusters with earliest spectral types less than B3 also prove to be good spiral tracers, as demonstrated by Becker and Fenkart (1970, 1971), Fenkart (1979), and Vogt and Moffat (1975). Figure 1 shows the local spiral structure obtained from these open clusters. Individual O stars are not perfect tracers, however. Lynds (1980a) found that only the hottest O stars trace the spiral arms; the later types occur in both the arm and interarm regions. A map of exciting stars in HII regions was made by Georgelin and Georgelin (1976). This will be discussed in §1.2. Long-period Cepheids (P>15 days) also tend to occur in spiral arms (Kraft and Schmidt 1963, Tammann 1970, Humphreys 1976, Efremov et al. 1981, and Berman and Mishurov 1981). Southern surveys reveal that A stars and early M stars show some concentration to spiral arms (Westerlund 1963, McCuskey and Houk 1971, McCuskey 1974); a small part of the Carina Arm is mapped out by A stars

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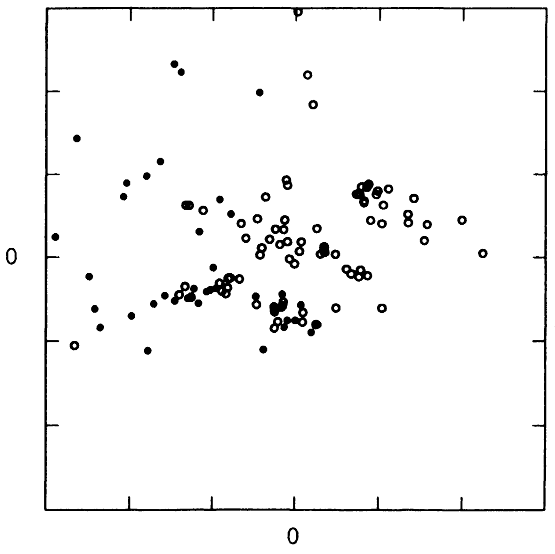

Figure 1. The local spiral structure is shown in the distribution of young open clusters plotted as open circles (Becker and Fenkart 1971) and closed circles (Vogt and Moffat 1975). The Sun is at (0,0). Tick marks are 2 kpc apart.

where no OB stars are present (Bok 1963). Other stars that appear to be loosely concentrated near spiral arms include Wolf-Rayet stars (Smith 1968), carbon N-stars (McCuskey 1970), and Be-stars (Kilkenny et al. 1975, Dolidze 1980).

1.2. Kinematic distances

Distances may also be determined from spectral-line velocities and the galactic rotation curve. This technique is usually applied to gaseous regions of HII, HI, and CO emission. Beyond the solar circle such distances are unambiguous, but inaccurate because of uncertainties in the rotation curve. Inside the solar circle, each velocity corresponds to two possible distances, so some additional information must be used to get the distance.

The pattern of optical HII regions in our Galaxy was observed by Georgelin and Georgelin (1976) and Georgelin, Georgelin and Sivan (1979); 20% of the distances were kinematic and 80% were spectrophotometric. Lockman (1979) and Downes et al. (1980) obtained kinematic distances to a large number of radio HII regions in the northern hemisphere. The near-far distance ambiguities were resolved by observing OH or H_2CO absorption features towards the HII regions. When an absorption line appears with a velocity much greater than that of the HII region, the HII region must be at the far kinematic distance. When no such high-velocity absorption is detected, then the HII-region distance is still ambiguous, but the near distance is usually assigned. The average error in this method is typically 10-20%, because (a) the systemic rotation curve is not perfectly well-known, (b) the emission-line velocity may have some random dispersion around the local systemic velocity, and (c) the emitting gas may be streaming along or between the spiral arms at unknown velocities. The distribution of HII regions obtained from these studies is shown in Figure 2.

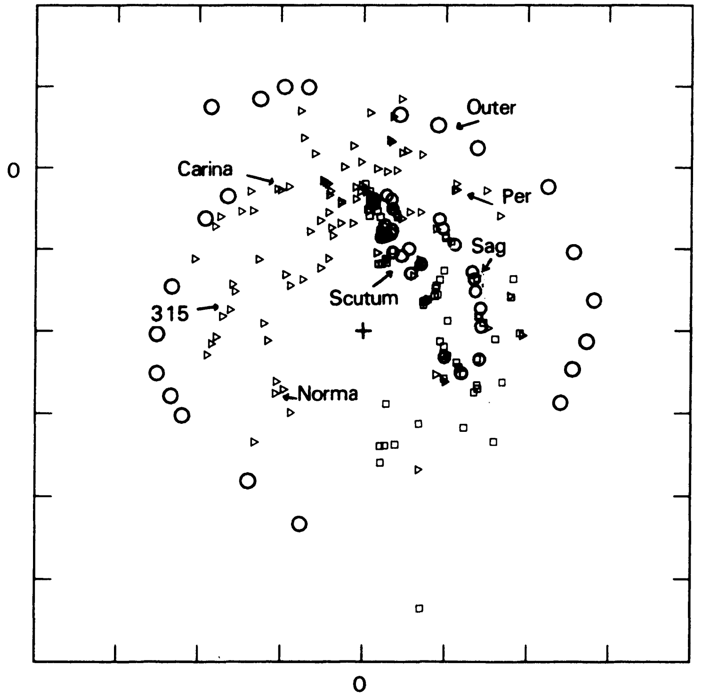

Figure 2. The global spiral structure is shown by the distribution of HI emission peaks (from Henderson, Jackson and Kerr 1982) plotted as large open circles, the CO clouds (Dame et al. 1983) plotted as small open circles, the optical HII regions (Georgelin and Georgelin 1976) plotted as open triangles, and the radio HII regions (Downes et al. 1980) plotted as open squares. The galactic center is indicated by the cross, and the Sun is at (0,0). Tick marks are 5 kpc apart.

Extensive HI surveys have been made of our Galaxy (Kerr 1968, and Burton 1974 and references therein, Weaver 1970, Weaver and Williams 1974, Kerr 1970, 1979). The distribution of HI in the outer regions of the Galaxy was determined recently by Henderson, Jackson and Kerr (1982). They obtained distances using a modification to the Schmidt rotation curve that accounts for N-S. The regions of maximum intensity, estimated from their contours, are shown in Figure 2. The structure in the inner region is more difficult to determine because of the distance ambiguity, and it also appears to be more complicated than in the outer region. The inner part of the Galaxy contains many spurs and branches, in addition to the prominent arms traced by the HII regions. The local distribution of HI is even less clear, because the random velocity dispersion in the local gas makes the kinematic distances very uncertain when the systemic radial velocity is small.

Carbon-monoxide emission from the northern hemisphere shows evidence for spiral-arm concentrations in the inner Galaxy. The recent study by Dame et al. (1983) indicates that the largest molecular clouds trace out the Sagittarius Arm and part of the Scutum Arm very clearly. Dame et al. resolved the distance ambiguity by using known distances to associated HII regions, H_2CO absorption features on the line-of-sight to background HII regions, and, for redundancy whenever possible, the cloud latitude extents for radii derived from a radius-linewidth relationship. The distribution of these large CO clouds is shown in Figure 2. Confinement of the general distribution of CO emission to spiral arms is not so obvious. Bash et al. (1977) and Cohen et al. (1980) proposed that most of the CO is in spiral arms, and, to the extent that most of the CO mass is in the largest clouds (Solomon and Sanders 1980; Dame 1983), their interpretation appears to be correct. Carbon-monoxide observations of the southern Galaxy also appear to show spiral arms (Robinson et al. 1982; Cohen 1985; Israel et al. 1985). However, the presence of emission between arms (Stark 1979), and the continuity of the terminal-velocity ridge on the longitude-velocity diagram of the first-quadrant emission, led Solomon et al. (1979), and Burton and Gordon (1978) to interpret the CO data as showing a more homogeneous distribution of intensity.

In the outer Milky Way, Kutner and Mead (1981, 1982, 1985) reported CO out to 27 kpc; they mapped an arm at a distance of 15 kpc from the galactic center, and an extension of the Perseus spiral arm in the first quadrant. Recent CO studies by Solomon, Stark and Sanders (1983) were unable to confirm many of these detections, however. Detections out to 18 kpc were reported by Blitz, Fich and Stark (1982), who noted that CO beyond 13 kpc was rare.

1.3. Tangent points from terminal velocities and continuum emission

Tangent directions to spiral-arm pieces may be found by noting the positions on terminal-velocity versus longitude curves where the slope suddenly changes. The difficulty with this method is that such inflections may sometimes result from a lack of emission at the tangent point, rather than from streaming motion in a spiral arm. Spiral-arm tangents for observations of HI (Henderson 1977) and CO (Robinson et al. 1982) have been determined using this method (see Table 1).

Spiral-arm tangent points may also be estimated from maxima in the radio-continuum intensity mapped along the galactic plane. The assumption is that the peak intensity corresponds to the edge of a spiral arm. This method has been applied by Mills (1963; see Table 1), Wielebinski et al. (1968), and Okuda (1985), who observed nonthermal and thermal radiation.

TABLE 1: Longitudes of Tangential Directions

Source	Ref.	Longitudes (degrees)						
HI	(1)	28-34	44-51	75-80	285-292	310-318	328-333	
CO	(2)	31	52			309	327 337 341	
HII	(3)	35	49		285	310	329	
continuum	(4)	0 13 27.5	50	80	262.5 282.5	310	327 337 344	

References: (1) Henderson (1977); (2) Robinson et al. (1982); (3) Georgelin and Georgelin (1976); (4) Mills (1963)

2. GLOBAL FITS TO THE OBSERVED SPIRAL STRUCTURE

2.1. Global models

The proposed global fits to the observations of our Galaxy include either two or four main spiral arms, with pitch angles of 5° to 27°. In order to discuss the details of different models, it is convenient to

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transform the map of Figure 2 into (log R, θ) coordinates (Figure 3). The names of particular regions of the Galaxy have been indicated on each figure for comparison. Logarithmic spiral arms will appear straight on this plot, with a slope that depends on the pitch angle. The (log R,θ) plot emphasizes that the Milky-Way spiral arms are represented only by short segments; there is no obvious and unambiguous way to join the pieces. Possible branching structures are evident. The following paragraphs will summarize various attempts to fit the data.

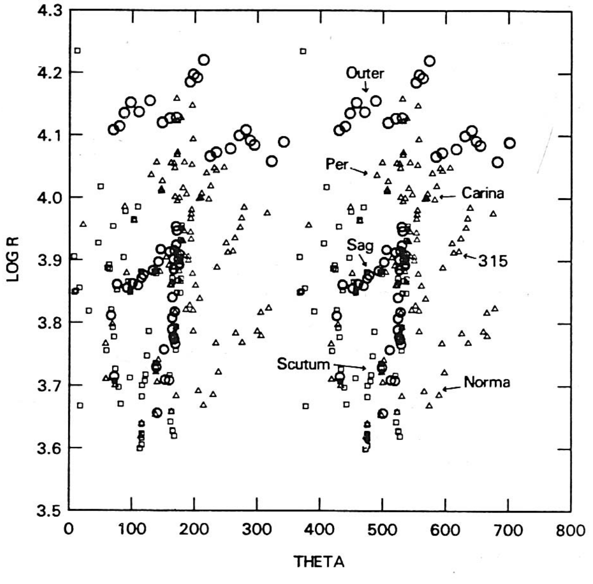

Figure 3. The global spiral pattern of Figure 2 is shown here in polar coordinates, with the same symbol convention as before. Logarithmic spiral arms would appear straight on this plot. The Sun is at log R = 4.0, theta = 180°.

A 2-arm spiral galaxy was the model proposed by many observers. Weaver (1970, 1974) suggested that a 2-arm global spiral with a 12°5 pitch angle could represent the major HI arms. Figure 4a shows straight lines representing his spiral fit superposed on the data points of Figure 3. He noted that the local and inner regions are complicated by many spurs and fragments. Simonson (1976) determined a global spiral pattern for HI data, with a pitch angle of 6-8° for 2 inner arms, which branch to multiple outer arms with pitch angles of 16°; the Orion arm appears as a spur with a pitch angle of about 20°. The Carina and Outer arms appear only as discrete arm segments in between the 2 major spiral arms, Sagittarius and Perseus. The Norma arm is suggested as an extension of the Sagittarius arm. Figure 4b shows his fit. Lockman (1979) obtained a 2-arm logarithmic spiral based on northern HI data; it does not fit the southern area as well. He noted that streaming motions would not affect his conclusions, since the HII regions which the model fits occur near the spiral-arm potential minima where streaming motions would be small. Models by Bash (1981), which include velocity dispersions and non-circular motions due to density waves, also show that a 2-arm global pattern might be consistent with the observations.

Several observers have interpreted the spiral structure as having four main spiral arms. Georgelin and Georgelin (1976) delineated 4 arm segments on the basis of their optical HII regions, as shown in Figure 4c. Henderson (1977) proposed a 4-arm global model with a 13° pitch angle and a 7 km s^{-1} streaming motion; this fit is shown in Figure 4d. He noted that inside the solar circle, the optical data near ℓ = 290° are not very well fit by this model. Henderson, Jackson and Kerr (1982) and Kulkarni, Blitz and Heiles (1982) also suggested models with 4 major arms in the outer regions. Kulkarni et al. interpreted the arms as being coherent spiral features 20-25 kpc long, with pitch angles of 22-27° based on the Blitz et al. (1982) revised rotation curve. Here, the Outer Arm (which they call Cygnus) and the Perseus Arm appear as major spiral arms. They could not interpret from their model whether the Orion feature is a spur or a long arm; its pitch angle was estimated to be 29°. They extended the outer 4-arm spiral in towards the 4-kpc region in this model, but noted that the extrapolated spiral does not fit the CO data in the inner regions everywhere (see Figure 4e). The preliminary analysis of CO data by Robinson et al. (1982) suggested 4 main arms with pitch angles of 11-13°. Three arms were indicated by the data, and the fourth, which occurs in an area difficult to map, was adopted to make the model symmetric (see Figure 4f).

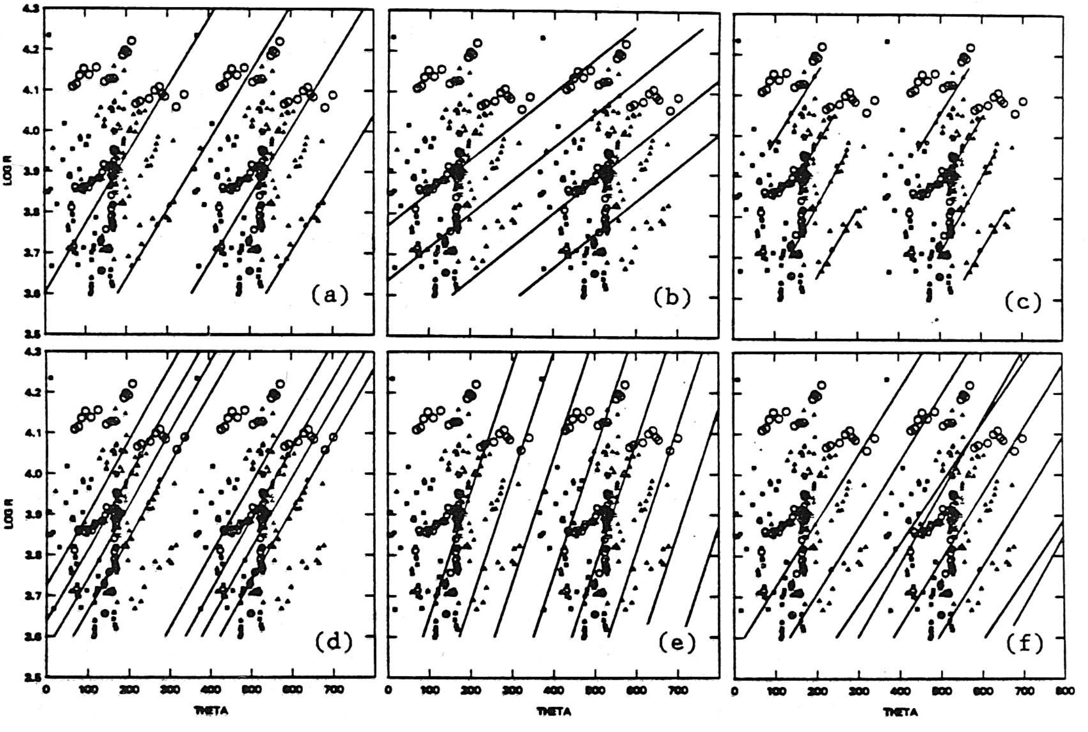

Figure 4. Fits to the spiral pattern are shown superposed on the data points of Figure 3. Details are discussed in the text. (a) Weaver (1970) 2-arm, i=12°.5; (b) Lockman (1979) 2-arm, i=6°.2 for inner regions; (c) Georgelin and Georgelin (1976) 4-arm, "eye-ball" fit; (d) Henderson (1977) 4-arm, i=13°; (e) Kulkarni et al. (1982) 4-arm, i=22-27°; and (f) Robinson et al. (1982) 4-arm, i=11-13°.

For the inner parts of the Galaxy, Quiroga (1977) fit HI and optical data to four arms, with pitch angles of 13-17°. Mills (1963) stated that 2, 3, or 4 arms are possible within the resolution of the continuum-emission data. In the extreme outer Galaxy, Sills (1982) has analyzed high-velocity gas in the first and second quadrants, which indicated a spiral arm with a pitch angle of 16-24° at a distance greater than 20 kpc.

2.2. Interpretation

The models just discussed show the confusion which prevails in considering spiral structure. All of the models are reasonably consistent with the observations. The difficulty is that the determination of a global pattern is not unique. So far, it is only possible to define discrete arm-segments; data in localized regions may be connected in unambiguous ways. The overall structure of the Galaxy must be extrapolated from a relatively small number of data points. It is clear that more data are needed in order to be able to distinguish between two, four, or even three-arm models, between large and small pitch angles, or between models with and without global symmetry.

The HI in the outer Galaxy, which is not subject to near-far distance ambiguities, provides a good clue to the overall structure of the Galaxy; it appears to have a roughly bisymmetric pattern. It is not clear whether this pattern extends to two or four arms in the inner region; the inner region does not show any obvious symmetry. It is possible that the Milky Way has only spiral-like pieces in the inner regions and a symmetric grand-design spiral in the outer parts; this is typical of galaxies like NGC 2903. In the next section, observations of external galaxies will be examined for comparison.

3. OBSERVATIONS OF SPIRALS IN EXTERNAL GALAXIES

3.1. Properties of external spirals applied to the Milky Way

Observations of spirals in nearly face-on external galaxies are unhindered by a poor vantage point; a knowledge of their properties might lead to a better assessment of the spiral structure of the Milky Way.

The Hubble type of a galaxy might be expected to give an indication of the pitch angle of its arms. De Vaucouleurs and Pence (1978) examined the overall photometric properties of the Milky Way, and classified it is an SAB(rs)bc II galaxy; such galaxies typically have pitch angles of $\sim$12-15°. Kennicutt (1981) found, however, that measured pitch angles in other galaxies correlate only weakly with bulge-to-disk ratios, and that the pitch angles have a large dispersion. Thus, the Hubble type of the Milky Way does not define our global pitch angle unambiguously.

Kennicutt (1982) and Block (1982) found that arm widths correlate with galaxy luminosity for Sbc and Sc spirals. Based on these results, we might determine an expected arm width for our Galaxy, which could aid in distinguishing between an arm and an interarm region. De Vaucouleurs and

Pence (1978) estimate a brightness $M_T^o(B) = -20.2 \pm 0.15$ for the Milky Way, which implies an arm width of some 820 ± 100 pc based on Block's data. This width is consistent with the width of the local arms in the Milky Way, as estimated from the distribution of young clusters.

HII regions have traditionally been used to trace spiral structure in other galaxies. Lynds (1970) made an optical survey of HII regions in external spirals, and Hodge (1969) determined the positions of HII regions for over twenty spirals based on Hα photographs. Hodge and Kennicutt (1983) have an atlas of HII regions in 125 galaxies, and Hodge (1982) summarizes the available data for HII regions in 223 galaxies. These HII maps show that, while HII regions give the impression of defining spiral arms, a plot of their distributions in galaxies reveals much interarm activity; indeed, spiral arms are often difficult to trace based on the positions of HII regions alone. As an example, Athanassoula (1978) determined, on the basis of HII regions, that the best-fit model to the highly inclined M31 galaxy was a 1-arm leading spiral. Rumstay and Kaufman (1983) examined the distributions of HII regions in M33 and M83 with excitation parameters greater and less than 115 pc cm^{-2}, and found that only the giant HII regions are concentrated in spiral arms. This may be true in our Galaxy as well (Fich and Blitz 1982).

Kennicutt and Hodge (1976), Boeshaar and Hodge (1977), and Anderson, Hodge and Kennicutt (1983) have examined correlation functions for HII regions distributed across spiral arms in NGC 628, NGC 3631, and NGC 4321, respectively, but have found no conclusive evidence for clumping. Elmegreen and Elmegreen (1983a) studied galaxies that happen to have regularly spaced giant HII regions and HI clumps, and found that the separation is about 20% of the galaxy size; this would correspond to 2 kpc in the Milky Way. Such giant HII regions and HI conglomerates have, in fact, been observed in our Galaxy. Twenty-nine large HI clouds ($M \sim 10^7 M_\odot$) in 4 arms were observed by McGee and Milton (1964), and 15 giant CO clouds ($M \sim 10^6 M_\odot$) in the Sagittarius Arm were mapped by Dame _et al_. (1983). The spacings between the giant clouds in our Galaxy are similar to what is observed in other galaxies.

Considère and Athanassoula (1982), Krakow, Huntley and Seiden (1982), and Iye _et al_. (1982) produced Fourier transforms of galaxy images in order to study spiral shapes and to determine the modes of the spiral waves that may be present. Kennicutt (1981) found that logarithmic as well as hyperbolic spirals may be present in a galaxy.

Dust lanes have long been recognized as good spiral tracers. Lynds (1970) mapped spiral features from dust lanes in 23 galaxies. It is therefore reasonable to examine whether dust might be useful as a tracer in our Galaxy. Holmberg (1950) and Lynds (1970) estimated the gas density of a typical dust lane to be ~ 10 cm^{-3}. Elmegreen (1980) determined that visual extinctions in external dust lanes are 1-2 mag; the typical extinction of the ambient medium perpendicular to the galactic plane is 0.5 to 1 mag. Thus, dust lanes represent only a relatively small compression of the local interstellar medium. Dust lanes are probably difficult to find in the Milky Way; we would not expect to see a dust lane stand out in any obvious way in a 21-cm survey, unless its velocity is peculiar because of streaming motions.

We can speculate about the external appearance of the dust lanes in our Galaxy. Lucke (1978) and Krautter (1980) determined that the cloud distribution within 2-3 kpc of the solar neighbourhood is patchy, and Lyngå (1979) suggested that the Milky Way does not have well-developed dust lanes. Further evidence for this deduction comes from external galaxies. Lynds (1980b) developed a Dust Classification (1 through 5) for Sbc and Sc spirals, based on the continuity of the dust lanes. The dust class was correlated with the number of bright HII regions. In our Galaxy, there are at least 25 optical HII regions with excitations in excess of 100 pc cm^{-2}, corresponding to a Lynds dust class between 2 and 3. Galaxies in this class have dark clouds or pieces of dust lanes associated with major spiral arms, but dust-lane continuity over no more than 30^{o} to 90^{o}.

Spurs are very common in external galaxies. While they do not contribute to the global pattern of a galaxy, they may be prominent regional features. Elmegreen (1981) found that spurs tend to jut outward from the edges of spiral arms, with pitch angles of $63^{o} \pm 12^{o}$. Weaver (1970) suggested that our Sun is in a spur jutting outward from the Sagittarius Arm with a pitch angle of $20-25^{o}$. However, optical data showing a gap between Sagittarius and the Local Arm led Humphreys (1976, 1979) to suggest that the local feature is probably a spur jutting inward from the Perseus Arm. Blaauw (1985) discusses details of the Local Spur.

Gaseous components of other galaxies might be expected to trace spiral structure, as they do in the Milky Way. Aperture-synthesis maps made at 21 cm have revealed detailed spiral features with resolutions of 20-30". These results will be discussed by Allen during this conference. Whether CO shows a spiral pattern is not as certain, since for external galaxies the CO beamwidth is generally too large. The effective resolution may be improved by using information about the known rotation of a galaxy, coupled with the observed CO velocities (Elmegreen and Elmegreen 1982a, Scoville and Young 1983). CO emission has been found to be associated with bright HII regions and possibly spiral arms in MGC 4321 (Elmegreen and Elmegreen 1982a), IC 342 (Rickard 1983), and M51 (Rydbeck 1985). However, CO appears to be stronger in the dusty interarm regions of NGC 5248 than in the bright spiral arms, and it is very strong in the dust lanes in NGC 1068 (Elmegreen and Elmegreen 1982a). CO has been mapped in a prominent southern dust lane in M31 (Boulanger, Stark and Combes 1981; Stark 1985), and it appears to be a better tracer of the spiral structure than HI; but this galaxy is too highly inclined to determine spiral structure unambiguously.

3.2. Flocculent and grand-design spirals

The global arm structure of spirals has prompted much attention. Sandage (1961) and Kormendy (1977) noted that many early-type spiral galaxies, like NGC 2841 or NGC 5055 (Figure 5a), have a patchy arm appearance. Woltjer (1965) suggested that such galaxies be referred to as "spiral-like" to distinguish them from grand-design spirals (e.g., NGC 4321, Figure 5b) with long, continuous arms. Elmegreen and Elmegreen (1982b) developed an Arm Class system (1-12) in order to rank the coherence and symmetry of spiral arms; the term "flocculent" was adopted to describe the spiral-like galaxies.

It is now possible to study spirals quantitatively with photographic surface photometry; Schweizer (1976) was the first to apply such methods to several galaxies. Talbot, Jensen and Dufour (1979, 1981) made a detailed study of M83. The derived azimuthal profiles did not reveal the transverse color gradients initially expected from spiral density-wave theory. Such effects are probably obscured anyway by epicyclic motions of the young stars (Bash 1979, Yuan and Grosbøl 1981). Efremov and Ivanov (1982) detected an age gradient in M31 based on long-period Cepheids; Humphreys and Sandage (1980) found only vague hints of an age gradient in some regions of M33, based on the distributions of young galactic clusters.

Strom, Jensen and Strom (1976) examined spiral structure in the red passband, and suggested that density waves should be sought in the near-infrared. Schweizer (1976), Jensen (1977), and Elmegreen (1981) made photographs of galaxies in the near-infrared passband; the underlying spiral is prominent in grand-design galaxies, but still is not present in galaxies that look flocculent in the blue.

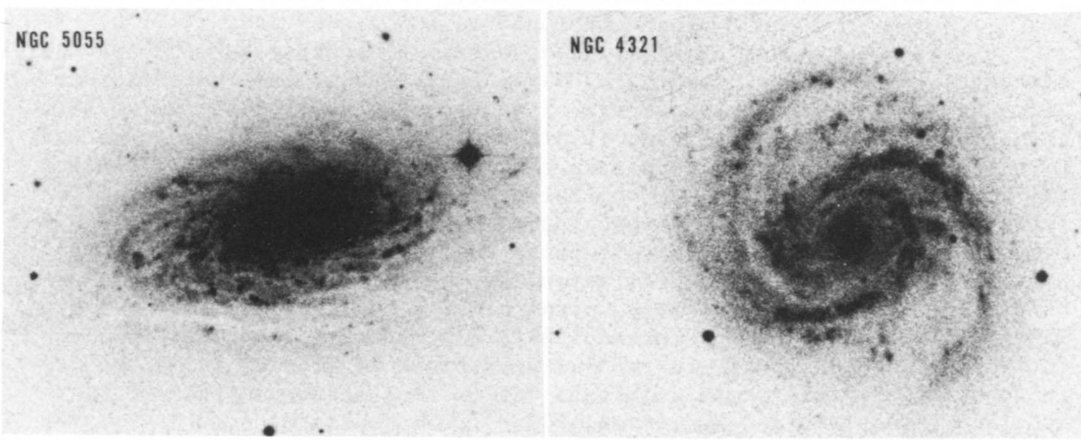

Figure 5. (a) Blue photograph of NGC 5055, a prototype of flocculent galaxies; (b) Blue photograph of NGC 4321, a prototype of grand-design galaxies.

Elmegreen and Elmegreen (1983b) acquired photographic surface photometry on 34 non-barred grand-design and flocculent spirals. For the grand-design galaxies, the arm-interarm contrast was found to be very large in the blue as well as in the near-infrared, often exceeding 1 magnitude. In flocculent galaxies, the arm-interarm contrast was large

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in the blue but small in the near-infrared. A plot of the arm-interarm contrast ratio for the blue divided by the contrast ratio for the near-infrared, versus the arm-interarm contrast in the near-infrared, reveals a pattern of arm features that correlates with arm class (see Figure 6). The large arm-interarm contrasts seen in the near-infrared for grand-design galaxies can be explained only if there is a significant stellar density enhancement in the arms. The enhancements are often larger than 40%, Elmegreen and Elmegreen (1983b). Flocculent spirals, on the other hand, may get their blue spiral structure from sheared star-forming regions. It therefore appears to be worthwhile to determine the distribution of older disk stars in the Milky Way in order to search for further clues of spiral structure.

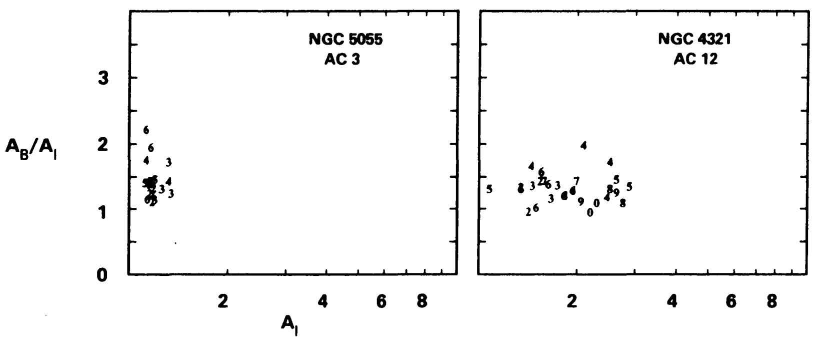

Figure 6. "Color-amplitude" plot for (a) NGC 5055 and (b) NGC 4321; the arm-interarm contrast in the blue divided by the arm-interarm contrast in the infrared is plotted versus the arm-interarm contrast in the near-infrared. Numbers correspond to tenths of R_{25}, the radius where the surface brightness is 25 mag arcsec^{-2}. Features to the right in the diagrams require density enhancements (Elmegreen and Elmegreen 1983c).

4. ORIGIN OF THE SPIRAL STRUCTURE IN THE MILKY WAY

A large number of spiral galaxies has been examined in order to understand how internal and external factors might contribute to spiral structure. These results may provide an indirect clue to the structure of the Milky Way galaxy.

Kormendy and Norman (1979) studied 54 spiral galaxies with known rotation curves, and found that galaxies with grand-design patterns had companions or bars. Madore (1980) found a weak correlation between the luminosity class of a galaxy and the presence of companions; spirals in small groups tended to be slightly more luminous than were isolated spirals. Thus, the presence of bars or companions appears to affect the way a spiral looks.

Elmegreen and Elmegreen (1982b, 1983c) determined spiral-arm classifications for over 300 spiral galaxies in the field and in groups. They found that, among non-barred galaxies, isolated spirals tend to be flocculent (68% ±10%), and spirals with companions tend to be grand-design (67% ±6%). Among barred or oval galaxies (types SB and SAB), 71% ±7% of isolated spirals, 72% ±4% of group-galaxy spirals, and 93% ±5% of binary-galaxy spirals are grand-design. Thus, symmetric spirals dominate disk galaxies except in isolated, non-barred, non-oval systems.

In a galaxy group, the percentage of non-barred spiral galaxies having grand-design structure correlates with the group-crossing rate. These results can be applied to the Local Group to estimate whether or not the Milky Way is likely to have a grand-design (symmetric) spiral. Four local galaxies are large enough to have been included in the surveys used in the previous studies (galaxies bigger than the SMC); M31 and M33 have a grand-design spiral structure. The Local-Group density is high enough that the Milky Way galaxy (and its companions, M31 and M33) has a 65% chance of being a grand-design spiral. The classification of the Milky Way as an SAB further strengthens the likelihood that our Galaxy has some kind of grand-design spiral over part of its disk. The Milky Way may have an arm class 7 or 9, which are the categories for NGC 2903 (Figure 7a), or M101 and NGC 1232 (Figure 7b), respectively.

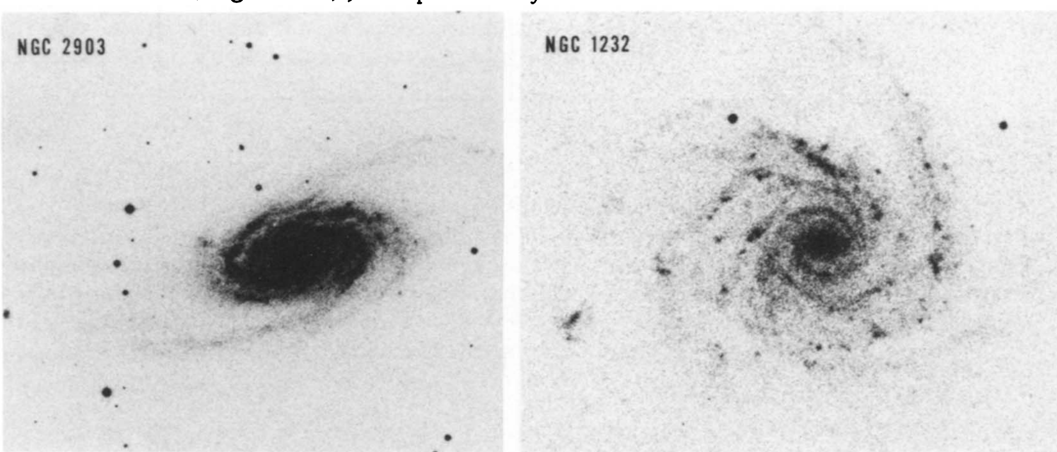

Figure 7. (a) Blue photograph of NGC 2903, which has a flocculent inner region and a grand-design outer region. (b) Blue photograph of NGC 1232, which has multiple arms and branches.

Toomre (1970) examined binary interactions and the possibility that the Milky Way structure was influenced by Local-Group galaxies. Fujimoto and Sofue (1976) also investigated the dynamical effects of the Large and Small Magellanic Clouds on the Milky Way. These calculations showed that at least the outer spiral structure of the Milky Way may be affected by its nearest neighbours.

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DISCUSSION

L. Blitz: Since much of the mapping of our Galaxy is incomplete, it is very difficult to know whether we are connecting spurs or pieces of real long spiral arms.

D.M. Elmegreen: That's right.

M.L. Kutner: The spiral structure in our Galaxy may be more easily discerned in the outer parts. Hence: "If you want to work out the spiral structure of our Galaxy, start at the outside and work your way in".

D.M. Elmegreen: I think that would be dangerous. Often the spiral structure in the outer part of a galaxy does not trace continuously into the inner part. In a galaxy like NGC 2903, for example, it would lead to erroneous results.

P. Pismis: It is reasonable to expect that the existence or not of spiral structure in galaxies depends in some way on the initial global parameters with which a galaxy gets started. One such parameter is the total mass. The total mass of a galaxy is related to the Hubble type, in the sense that it decreases on the average as one goes from the Sa's to the Sc's and on to the irregulars. A. Meisels (1983, Astron. Astrophys. 118, p. 21) has recently reached a similar conclusion, without being aware that the relation I mentioned had already been discussed some five years earlier (P. Pismis and L. Maupomé 1978, Rev. Mexic. Astron. Astrofis. 2, p. 319). Thus there is independent confirmation that statistically the average masses are related to the morphology of spirals, although the scatter is large. It is worth emphasizing that spiral structure tends to be well developed in a fixed mass range and that below 10^{10} solar masses spirals are not well developed; they are rather of the Magellanic type at best. In addition it is found that the average mass of barred spirals falls below that of "normal" spirals for the same Hubble type.

D.M. Elmegreen: I agree that Hubble type may be loosely correlated with galaxy mass. But we find (Elmegreen and Elmegreen, 1982b) that the spiral-arm class, which is a measure of the symmetry and continuity of the spiral arms, is independent of Hubble type and therefore apparently independent of galaxy mass (except for the very-low-mass systems which are Magellanic types). Galaxies of Hubble types Sa through Sd may have all ranges of arm class, from flocculent to grand-design. For example, NGC 5055 is an SAbc which is very flocculent, and yet M51 which is also an SAbc has a grand design. There has also been some theoretical conjecture that the presence of a grand-design spiral structure may depend on the ratio of disk mass to halo mass. While this may be true in a statistical sense, it cannot be true for every galaxy. I call attention to Carignan's paper in Section II.1; he finds evidence that NGC 7793, which is a classic flocculent galaxy, apparently has no halo, whereas we might have expected it to have a large one. So I think it is not just the mass dependence that determines spiral structure.

R.J. Allen: I would like to ask a question about the change in morphology with position in a galaxy. We see in the inner regions of M101 the flocculent kind of spiral arms, and in the outer regions the heavy spiral arms with lots of HII complexes. Would you believe that the character of spiral structure is correlated with the surface density of dust?

D.M. Elmegreen: Some galaxies have inner flocculent structure and outer grand-design (e.g. NGC 2903), some have inner grand-design and outer flocculent structure (e.g. NGC 6946), some have grand-design everywhere (e.g. NGC 5194), and some are flocculent everywhere (e.g. NGC 5055). I have not yet noticed any clear correlation between the type of spiral structure and the column density of the dust.

T.M. Bania: To my eye the dominant patterns on your log R vs. Θ plot of spiral tracers for the Milky Way are directly vertical. Would you care to comment?

D.M. Elmegreen: The feature to which you are referring is the one near $\theta = 180°$. Nobody really knows what it is. It might be a spur. Other equally good arms have a more normal pitch angle of some 12°. Spurs with high pitch angles (about 60°) are also seen in external galaxies.

K.S. de Boer: I wish to point out that you build a second model on top of a first model by making fits in your Θ-log R diagrams. All radial distances from 21-cm HI data and for distant HII regions were derived by assuming a rotation curve for our Galaxy. Then you try to fit a second model: a logarithmic spiral!

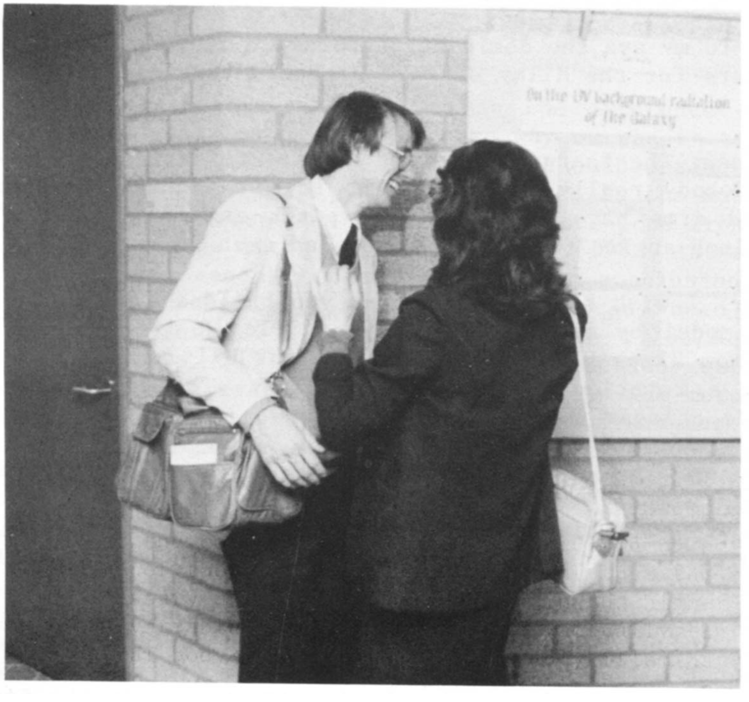
D.M. Elmegreen: Of course all models of spiral structure require distance determinations, and, as I mentioned, the kinematic distance determination may contain systematic errors. I am not using the θ - log R plots to build a second model; I am merely using them as a convenient way of illustrating the distribution of spiral-arm tracers.

F.H. Shu: I wonder how many independent parameters it takes to characterize a spiral galaxy. Two are obvious: Hubble type and Van den Bergh luminosity class. A third may also be important, namely the fractional gas content. Do you know if there is a systematic difference in the gas content of flocculents and grand-designs?

D.M. Elmegreen: Yes, I think that is an important point. We have looked at that a little bit, but not in detail.

R.G. Carlberg: Would you care to say anything about the lifetime of any particular pattern?

D.M. Elmegreen: The correlation between group-crossing time and the fraction of galaxies with grand-design structure (Elmegreen and Elmegreen, 1983c) allows for the possibility that grand-design spiral patterns are transient. A galaxy in a flocculent state could go into a grand-design state for some time after an external perturbation. By the way, regarding Dr. Pismis' comment, this possible transience is another reason why we think that grand-design spirals should not correlate with galaxy mass.



Debra M. (right) and Bruce G. Elmegreen CFD