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THE SHAPES OF SPIRAL ARMS ALONG THE HUBBLE SEQUENCE

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ABSTRACT

Measurements are presented of the shapes and pitch angles of the spiral arms in a large set of nearby Sa–Sc galaxies. The question of the mathematical forms of the spirals is shown to be irrelevant for the majority of real galaxies. Neither logarithmic nor hyperbolic spirals accurately represent galactic arms, but, within the limitations set by arm distortions both forms may serve as adequate interpolation functions in normal spirals. The arms in strongly barred galaxies are systematically distorted. Measured pitch angles for 113 objects correlate weakly with arm structure and bulge-to-disk ratio, suggesting that Hubble's classification criteria are less tightly coupled than previously believed. The maximum rotation velocity in a galaxy is shown to be well correlated with arm pitch, suggesting that the shape of the spiral pattern is dictated by kinematic parameters, independent of the physical origin of the arms. The arm pitch appears to be tied to the absolute value of the rotation velocity, not to the angular velocity, as might be expected in material arm pictures.

I. INTRODUCTION

Broad correlations between the spiral structure of a galaxy and its morphological type have been observed, but not understood, since the pioneering work of Hubble (1926) and van den Bergh (1960). These relationships lie at the foundation of the Hubble and luminosity classifications of the spiral galaxies, and their explanation remains as one of the primary challenges to theories of spiral structure and galaxy evolution. Yet aside from the early work of Danver (1942), no attempt has been made to establish systematically the dependence of spiral structure on galaxy morphology and dynamics.

This paper reports an effort to provide hard data on the morphological trends in spiral structure, arm shape, and pitch, along the Hubble sequence. Two recent developments in the field have motivated this work. Proponents of both the density wave (Roberts, Roberts, and Shu 1975) and the stochastic (Seiden and Gerola 1979) theories have successfully accounted for the qualitative behavior of spiral arms as a function of Hubble type; the success of two such radically different models in accounting for the same observed phenomena suggested that a more quantitative comparison of observed and theoretical properties was in order. Data of this kind are also relevant to another, strictly empirical controversy. Recent studies of galactic structure and evolution in different environments have made use of comparisons of integrated properties and classifications of spirals from a variety of published sources. In most cases the published Hubble type has been regarded as an objective, monotonic parameter, despite the fact that it relies on at least three, not necessarily independent morphological criteria—spiral arm morphology, disk resolution, and bulge-to-disk ratio. Different classifiers (e.g., de Vaucouleurs, de Vaucouleurs, and Corwin 1976; van den Bergh 1976; Sandage and Tammann 1981; Thompson and Gregory 1981, in preparation) weight these parameters differently, and a major goal of this study is to compare the three criteria in order to reveal any subtle biases which may be present when the different sets of Hubble types are indiscriminately mixed with each other.

In order to address these questions, arm shapes and pitch angles have been determined for a large sample of nearby spiral galaxies. Section II presents an updated analysis of the mathematical forms of spiral arms, a question relevant to recent theoretical work (Seiden and Gerola 1979). Measurements of the average pitch angles of the spiral arms in 113 nearby spirals are discussed and presented in Sec. III. Those data are then used in Secs. IV and V to establish the dependence of the spiral structure on morphological type, luminosity, and kinematics. The implications of these results for the interpretation of the Hubble classification of galaxies will be discussed as well. Other papers in this series will deal explicitly with the predictions of theoretical models of spiral structure (Kennicutt and Hodge 1982) and with the luminosity dependence of spiral structure and the luminosity classification (Kennicutt 1981).

II. ANALYSIS OF ARM SHAPES

The question of the mathematical form of spiral arms predates the recognition of the spirals as extragalactic

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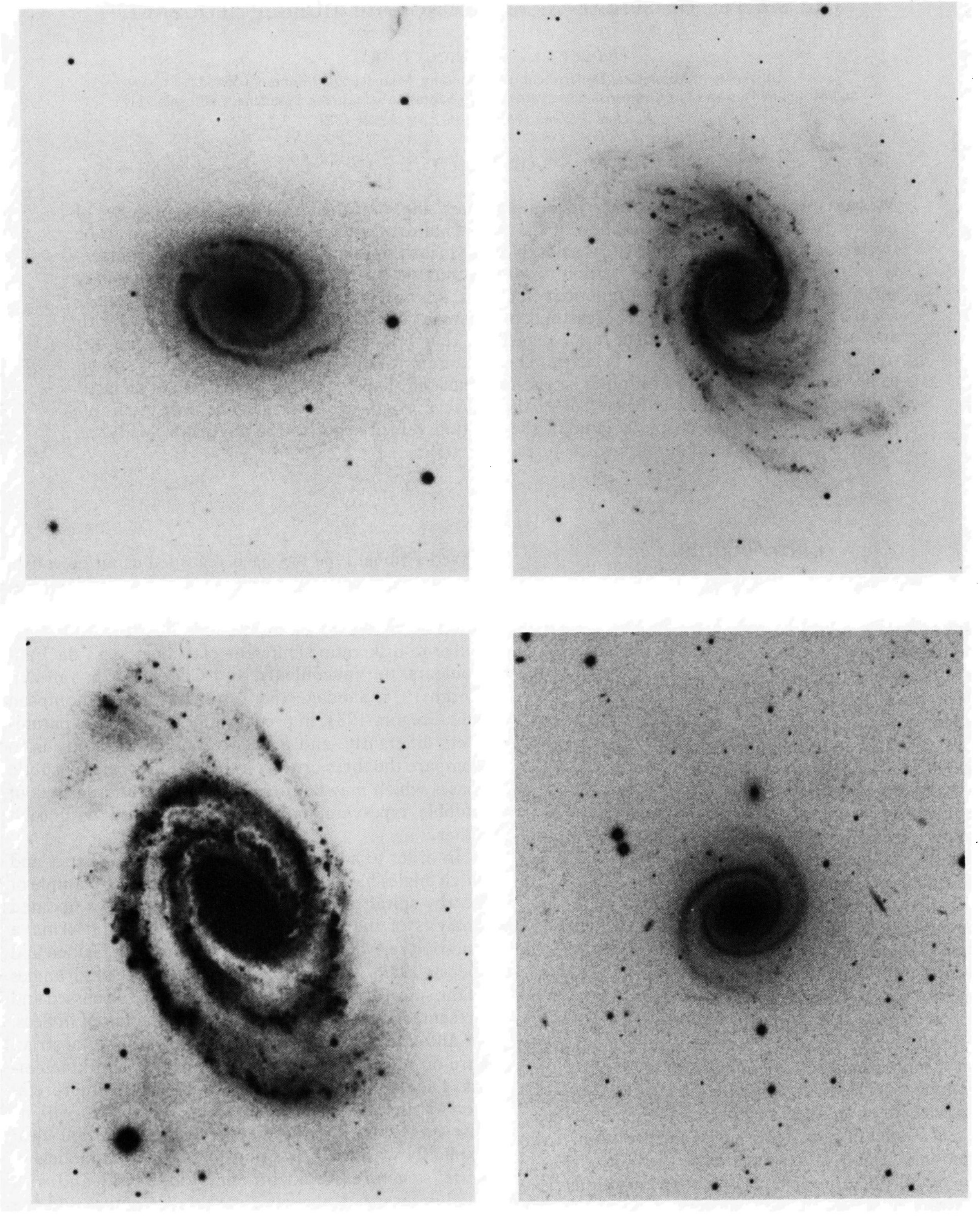

FIG. 1. The four highly regular spirals analyzed for arm shape. The reproductions of NGC 1357, 1566, and 7096 are from du Pont 2.5-m plates obtained by the author. The photograph of NGC 5364 (PH-193-MH) is reproduced from the *Hubble Atlas of Galaxies* by Allan Sandage (Carnegie Institution of Washington Publ. No. 618, 1961). The faint background in NGC 5364 is an artifact of the reproduction process.

TABLE I. Spirals measured for shape.

NGC	Type	i	pa	Source[a]
628	Sc	35	0	1
1357	Sa	40	80	2
1398	SBab	48:	90:	1
1566	Sc	30	20	2
3504	Sb/SBb	0	–	1
3504	Sb/SBb	55	150	
5194	Sbc	35	42	1
5364	Sc	47	25	1
7096	Sa	30	125	2
7479	SBbc	35:	35:	2

[a](1) Sandage (1961); (2) this paper.

objects (von der Pahlen 1911; Bottlinger 1919; Groot 1925; Reynolds 1925). It has recently resurfaced in a theoretical context. The density wave spirals (Roberts, Roberts, and Shu 1976) are usually well represented by logarithmic spirals with slowly changing pitch

$$r = r_0 \exp[\kappa(r)\phi],$$

$$\kappa(r) = \cot \mu(r),$$

where the pitch angle μ generally varies by only a few degrees. Material arms, on the other hand, such as those of Seiden and Gerola (1979), possess a nearly hyperbolic form

$$r(\phi - \phi_0) = \text{const} \times V_{\text{rot}}(r)$$

dictated solely by the rotation curve (V_{rot}) of the galaxy in question. For very long spirals ($\Delta\phi \gtrsim 360°$) these two forms are easily distinguished, but in most galaxies, especially those with the short arms most resembling the stochastic models, the two shapes are not easily separated. Danver (1942) studied a sample of 98 nearby (mostly Sc) spirals, and concluded that the logarithmic form (with constant pitch) matched the arms better than any other on average, but Danver's poor plate material, combined with the patchy structures of the arms in his galaxies, have left this result in some question. A broader and much better set of material is now available and the question can be more definitively addressed.

a) Normal Spirals

Detailed determinations of the arm shapes were made for six normal spirals. NGC 1357, 1566, 5364, and 7096 possess some of the most symmetric and regular spiral patterns that can be found among the Shapley-Ames galaxies. This highly biased sample was selected intentionally; if for these beautiful objects there exists no preferred mathematical form, then the question is moot for all. In addition, two other galaxies, M51 and NGC 628, were included as examples of more representative cases. NGC 1357, 1566, 5364, and 7096 are illustrated in Fig. 1.

Table I lists the sources of data and the derived arm properties. For each galaxy the arms were traced directly from photographic enlargements; the regularity and prominence of the arms in these galaxies minimized any personal prejudice in the process. The geometries were then corrected for inclination effects, using Danver's (1942) iterative procedure. An initial estimate of the inclination and pitch angle was used to orient the spiral to a face-on geometry, and any residual sinusoidal deviations in the arm shapes were then used to make small corrections to the derived orientation. The procedure is illustrated in Fig. 2 for NGC 5364, where the initial "guess" was made on the assumption (clearly incorrect in this case) that NGC 5364's internal ring is circular. The orientation procedure is critical, because errors can masquerade for small-scale arm distortions (Stock 1955). Again the regularity and length of the arms in the present sample made the process much easier than is typically the case (Danver 1942; Kennicutt and Hodge 1976, 1982). The resulting orientations are listed in Table I. In general I found that I could measure the inclination and position angles in this way to an accuracy of $\pm 2°$–$5°$, limited by the arm distortions as discussed below.

The mathematical forms of the spiral arms now could be determined, by plotting them in transformed coordinates, linearized for each form in question. For this analysis two functions were considered, a logarithmic spiral of constant pitch (linear in log r vs ϕ), and the hyperbolic form, linear in $r\phi$ vs r. It quickly became apparent that neither form precisely represents the arms, even the most regular ones, and that in fact small-scale distortions preclude the possibility of *any* universal shape for galactic spirals. The situation is illustrated by Figs. 2–4. Figures 3 and 4 display the arms in logarithmic and hyperbolic coordinates, respectively, while Fig. 2 details the analysis of NGC 5364. A number of significant (and sometimes surprising) results are apparent.

(1) None of the spirals is precisely described by the logarithmic or hyperbolic forms. This result is especially significant because the orientation in Table I and Figs. 3 and 4 were chosen to minimize the departures from linearity (see below). The true inclinations and pitch angle of the galaxies in question may differ slightly from those chosen, in which case the arm distortions are really larger.

(2) No systematic behavior in the arm distortions is

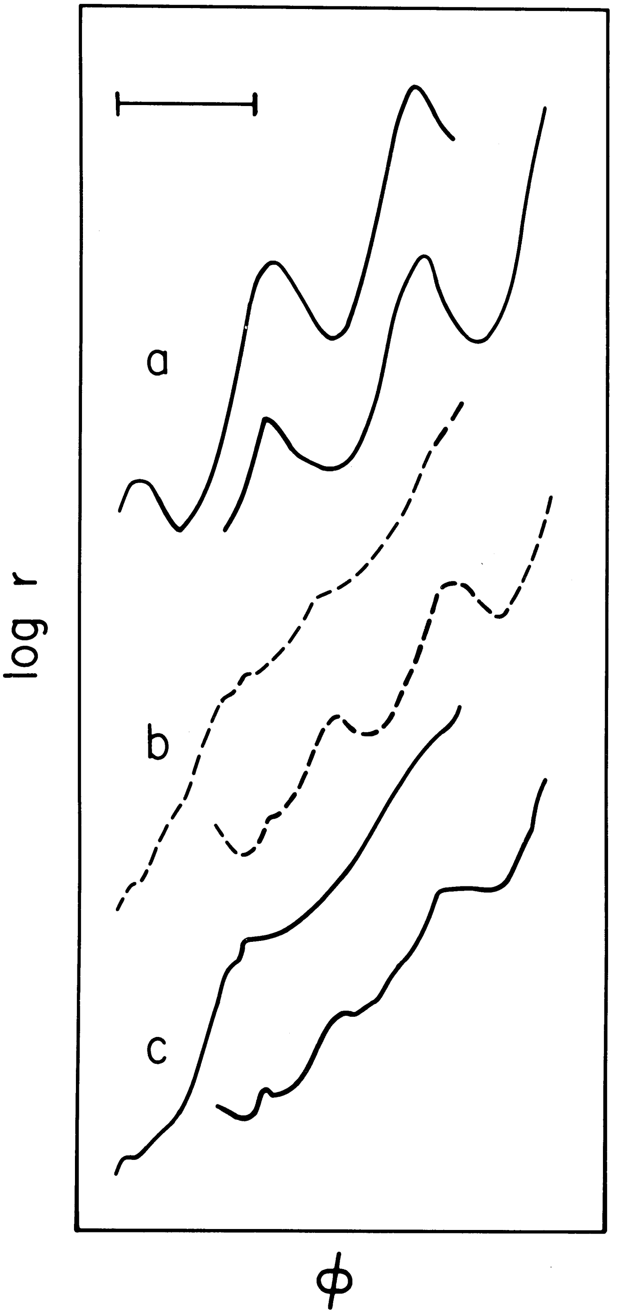

FIG. 2. Derived geometries for the pair of spiral arms in NGC 5364, for three possible orientations. The top plot is for an orientation in which the inner ring is presumed to be circular ($i = 56°, p = 45°$). The middle orientation is optimized to yield a smooth fit to the north (upper) arm ($i = 40°, p = 20°$). The lower plot is for Danver's orientation ($i = 47°, p = 25°$).

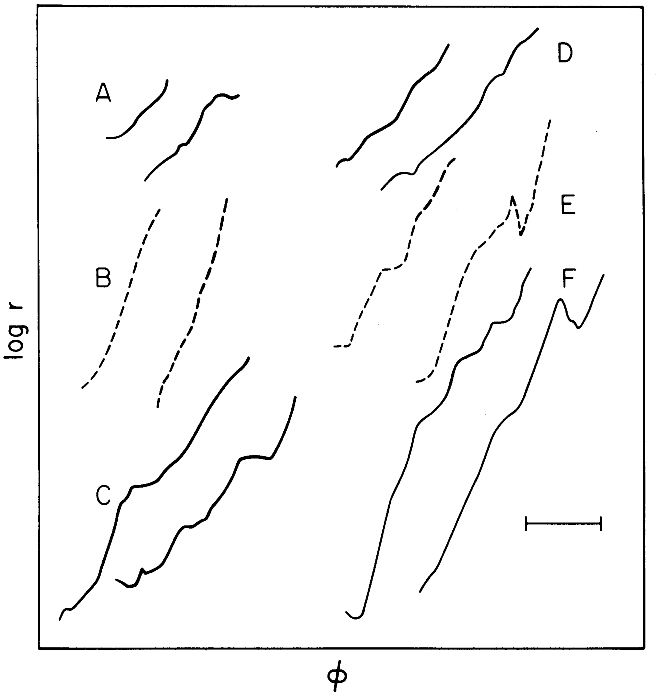

FIG. 3. Arm pairs in logarithmic spiral plane, for the orientations listed in Table I. (A) NGC 1357; (B) NGC 1566; (C) NGC 5364; (D) NGC 7096; (E) NGC 628; (F) NGC 5194. The horizontal bar denotes an angular interval of 180°.

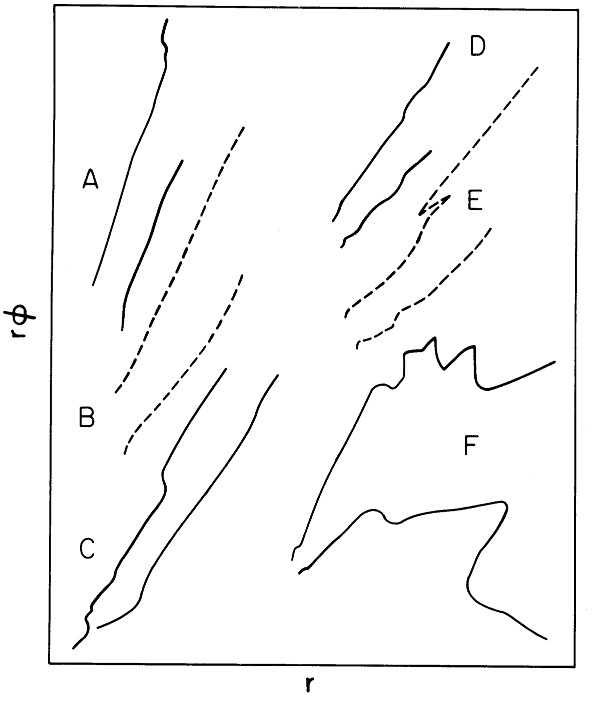

FIG. 4. Arm pairs plotted in hyperbolic spiral plane. See Fig. 3 for identification of individual galaxies.

evident, e.g., the deviations cannot be explained as being due to a systematic opening or tightening of the arms with radius. The distortions appear to be random in nature, on both small and large scales.

(3) *Both* logarithmic and hyperbolic forms are crudely representative of the real arms. Apparently over the short lengths of the real spirals ($\lesssim 360°$) the small-scale distortions mask any distinctions between the two forms.

Figure 2 shows that the conclusions derived above are not simply an artifact of incorrectly measuring the orientation of the galaxies in question. The sinusoidal residuals produced by an incorrect inclination and/or pitch angle are easily detected in NGC 5364 at the $\pm 10°$ level. Figure 2 also indicates that if the geometry is optimized for one arm, the other will show pronounced distortions. This behavior, observed for all six spirals studied, shows that the distortions are real, and suggests that they limit the accuracy to which the orientation itself can be determined, to $\pm 2°$–$5°$, depending on the regularity of the pattern.

Since the arms in the spirals studied here possess no preferred analytical shape, the issue of arm shape in spiral galaxies overall is a moot one. While it is possible that the arm distortions observed may result from underlying dynamic distortions which might be accounted for by a particular spiral arm model, the observational difficulties encountered in precisely determining the geometry preclude the possibility of "testing" the density wave or stochastic models on the basis of arm shape alone. The results above *do* show, however, that the logarithmic (and perhaps the hyperbolic) form does serve as a meaningful interpolating function for spiral arms, as argued earlier by Danver (1942). As a consequence it appears that for statistical comparisons of galaxies the average pitch angle of the spiral pattern may serve as a meaningful parameter.

b) Barred Spirals

The conclusions derived in Sec. II a for normal spirals do not necessarily apply to arms in strongly barred galaxies, or to galaxies possessing strong "lens" components (Kormendy 1979). As has been pointed out by Kormendy, the spiral arms in these galaxies show systematic distortions which are often aligned with the inner bar structure, suggesting that the outer disk "feels" the potential of the bar. From an operational point of view, the distortions make it very difficult to derive the orientation and true shapes of the arms in the barred galaxies; the true ellipticities of the various galaxy components (needed to derive the orientation) are not known. Whatever the orientation, however, the arms cannot be fitted to well behaved spirals. Figure 5 displays log r-ϕ plots for arms in three barred galaxies, NGC 7479, 1398, and 3504, for the "best-fitting" orientations, as listed in Table I. The outer arms of NGC 3504 are plotted for two possible orientations, face-on (i.e., the outer disk is circular) and inclined 55° (i.e., the inner disk is round). In either case the arms are distorted. Huntley's (1978) calculations suggest that the proper interpolating form for barred spirals may be the linear, or Archimede's spiral. When the objects considered here were plotted in the linear r-ϕ plane, however, the distortions were still present, although uncertainties in the orientation weaken these conclusions somewhat. A more definitive comparison of models and observations

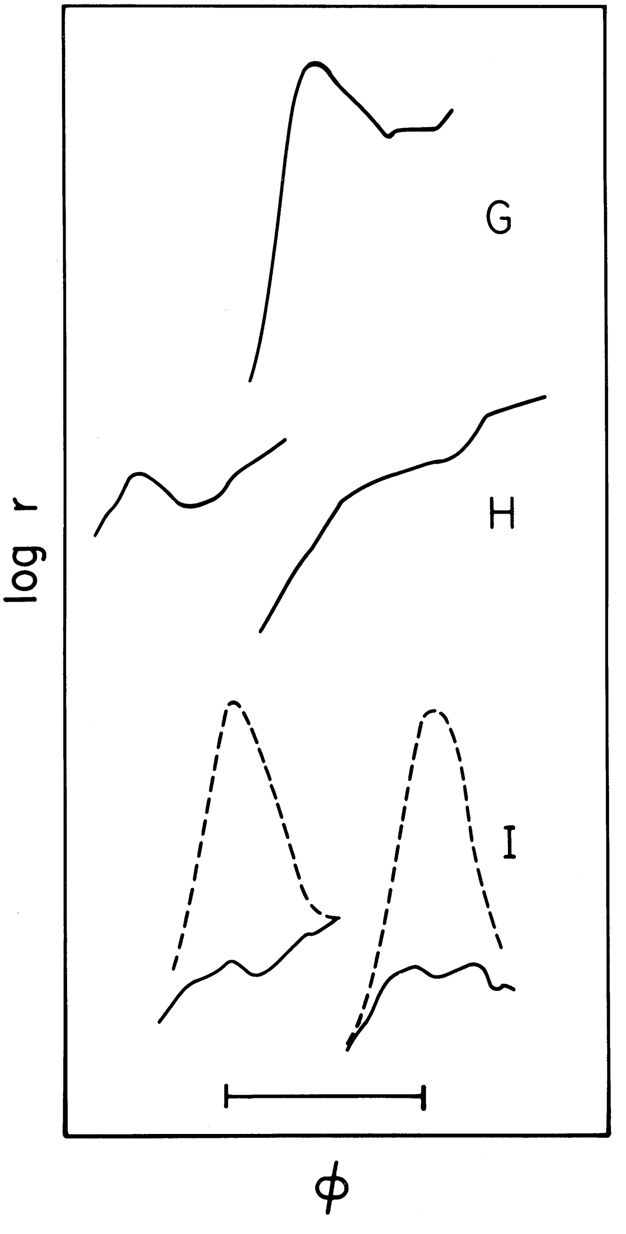

FIG. 5. Arms in three barred spirals, plotted in logarithmic plane, for "best-guess" orientations listed in Table I. (G) NGC 7479; (H) NGC 1398; (I) NGC 3504. For the latter, two possible orientations were considered: face-on (lower) and inclined so that the lens of the galaxy is round (upper). The horizontal bar denotes 180°.

will not be presented here. For present purposes it suffices to emphasize that barred spirals appear to have a shape that is distinct from those in normal spirals. The observed distortions are not unexpected (e.g., Huntley 1978; Huntley, Sanders, and Roberts 1978), but a careful comparison of these models with the observations will require careful treatment of the orientation problem.

III. MEASUREMENT OF PITCH ANGLES

a) Data

In order to cover the maximum range of galaxy types and morphologies, a variety of source material was utilized. Hα photographs often isolate the arms with a minimum of ambiguity (Kennicutt and Hodge 1982), and H II region data on 26 galaxies from the compilation of Hodge and Kennicutt (1982) were used to fit the orientations and shapes of the spiral arms using the methods described earlier. The range of galaxy types which can be studied using the H II regions is limited, however, to late-type systems with large numbers of resolved H II regions. In order to extend the breadth of the sample, measurements of broadband blue photographs were also made from a variety of sources (Sandage 1961; Sandage and Brucato 1979; Sandage and Tammann 1981; and for a few objects the Palomar and ESO/SRC surveys). A special set of 17 large-scale plates of Sa–Sab galaxies obtained by the author was measured to extend the results to the faint spiral arms in those early galaxies. Otherwise the galaxies measured in integrated light were selected chiefly on the bases of the availability of suitable material and a spiral pattern regular enough to be accurately measured. The latter criterion introduces a small bias into the results which will be dealt with in Sec. III c.

b) Comparison of Dust, Hα, Blue, and Red Arms

Before proceeding it is important to establish to what degree (if any) the derived arm shapes are dependent on the particular arm component measured. In the density wave picture (e.g., Roberts 1976; Elmegreen 1979) the dust lanes and radio continuum ridges are thought to best trace out the spiral shocks, while the underlying red continuum arms (if present) may best trace the underlying stellar density wave. In the stochastic picture (Seiden and Gerola 1979) it is the stellar arms which are most readily modeled. From a strictly observational point of view, however, Lynds (1970, 1974) has argued that the shapes of the dust, H II region, and continuum arms are very similar, suggesting that measurement of any component may suffice in statistically parametrizing the spiral pattern.

In order to ensure that the pitch angle measurements made here on the basis of Hα and/or blue continuum arms were not seriously biased, independent measurements were made of the H II region, dust, and blue-visual broadband arms in three spirals, NGC 1566, 5236, and M51. For M51, high-quality data on the underlying red continuum (Zwicky 1955; Schweizer 1976) and nonthermal radio continuum arms (Mathewson, van der Kruit, and Brouw 1972) are also available, and they were compared as well. The results of these comparisons are summarized in Table II. For each separate arm component the arm coordinates (rectified to face-on orientation) were plotted in the log r vs ϕ plane, and fitted to the best straight line to determine the average pitch angle. The mean values, averaged over the two main arms in each galaxy, are listed in Table II.

If the three galaxies analyzed are representative, then there appears to be no significant difference in the arm geometries determined from the integrated light, the H II regions, or the dust. There is a suggestion that the dust arms may be slightly more open; in the spirals measured the dust lanes consistently occur on the insides of the optical arms, and consequently a difference of a degree or two in pitch is expected. There is a tantalizing indication that the underlying red arms in M51 may be significantly displaced from the blue/Hα/dust arms (the reader is referred to the photographs of Schweizer 1976 and Zwicky 1955 for an illustration of the effect), and the measured pitch of those red arms is significantly different. Part of the discrepancy, however, may arise because the red arms cannot be traced over the entire region visible in the other components, as shown in Table II. Further exploration of the relationship between the visible arms and the "underlying" stellar arms must await a broader survey of the infrared structure of spirals (D. Elmegreen, in progress). For the purposes of the present analysis, however, it appears safe to use the optical arm tracers, either Hα or continuum, to parametrize the shapes of the spiral patterns.

c) Results

Table III lists the average pitch angles and estimated uncertainties for 113 spiral galaxies. As mentioned in Sec. III a, the data set was restricted to well resolved, nonbarred, or weakly barred galaxies with unambiguously measurable spiral patterns.

TABLE II. Individual arm components.

NGC	Pitch angles: blue	dust	H II	red	radio
1566	22 ± 2	24 ± 2	22 ± 2		
5194	14 ± 2	15 ± 2	14 ± 2	11 ± 2	14 ± 2
5236	15 ± 3	17 ± 3	15 ± 3		

TABLE III. Measured pitch angles.

NGC	Pitch/range
157	19 ± 4
210	11 2
262	11 1
289	14 4
300	25 3
309	17 2
488	5 1
495	8 2
514	18 2
598	31 5
628	15 2
718	4 2
864	16 3
895	22 3
918	18 2
925	25 2
1042	13 3
1079	7 2
1084	18 3
1097	17 4
1187	14 4
1232	15 4
1350	7 2
1357	8 1
1365	18 3
1398	6 2
1566	22 2
1832	17 3
2217	3 1
2223	16 4
2336	18 4
2403	21 4
2442	28 3
2525	17 4
2543	13 2
2763	18 4
2835	20 2
2857	13 1
2903	13 5
2997	14 2
3001	14 3
3031	12 2
3081	1 1
3184	17 3
3185	0 1
3261	13 2
3294	20 3
3338	13 2
3344	15 2
3346	14 3
3347	21 3
3358	6 2
3464	12 2
3486	22 4
3521	14 3
3631	17 4
3783	7 1
3938	12 3
3992	11 2
4030	12 2
4254	22 4
4303	13 2
4321	15 3
4378	4 1
4394	10 2
4450	10 2
4454	3 1
4487	26 4
4501	15 3
4504	21 3
4535	18 3
4548	16 4
4579	7 2
4622	7 2
4654	16 3
4725	7 1

TABLE III. (continued)

NGC	Pitch/range
4826	7 ± 2
4939	11 2
5005	10 3
5033	19 3
5055	11 3
5068	22 4
5085	12 2
5101	7 2
5194	15 2
5236	16 2
5247	28 4
5364	9 2
5371	14 4
5457	25 4
5676	13 2
5701	7 2
5962	11 2
5985	9 2
6118	14 3
6384	11 2
6412	16 3
6654	5 1
6699	12 3
6477	15 2
6753	10 2
6814	13 2
6946	28 4
7020	0 1
7096	8 2
7125	19 3
7126	11 2
7205	13 3
7217	4 2
7331	14 3
7743	6 2
7753	13 2
I342	19 5

Two methods of measurement were employed. For approximately half of the sample the orientation and arm pitches were derived using the fitting procedure described in Sec. II. For galaxies with fairly long arms ($\gtrsim 270°$) the pitch could be determined independent of orientation effects by making 180° cuts across the arms (at intervals of 20°–30°) and averaging the results. In both cases, the pitch angles of individual arms could be measured to within an uncertainty of typically $\pm$ 1°–3°, depending on the regularity of the arms. For most of the galaxies, however, this measuring error was small compared to the intrinsic dispersion in the pitch angles of the arms themselves in a given galaxy. For the galaxies measured here, and for 98 spirals measured by Danver (1942) the pitch angles of the two major arms differed by an average of 5°, a value much higher than the typical measuring error. Consequently the average pitch angles derived are only meaningful at a level of typically $\pm$ 2°–4°. This uncertainty has been listed for each measured spiral in Table III.

Before discussing these results it is useful to compare them with the older measurements of Danver (1942). Thirty-eight of the galaxies listed here were previously measured by Danver, and the average pitch angles are

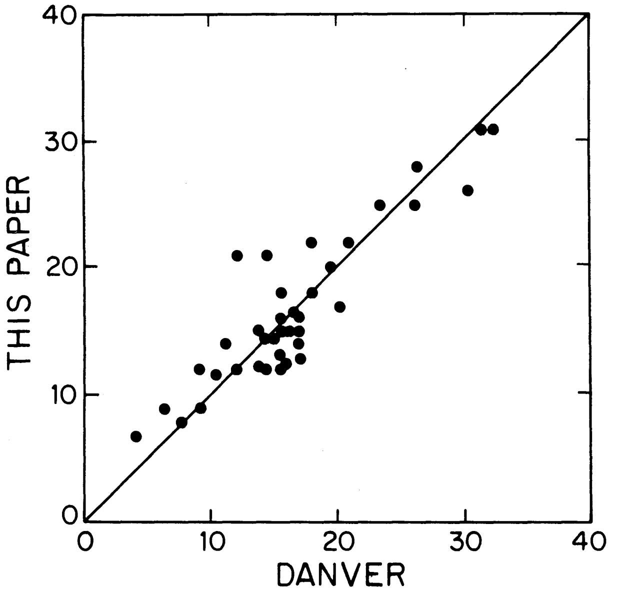

FIG. 6. Comparison of pitch angles derived here with earlier measurements of Danver, for galaxies in common.

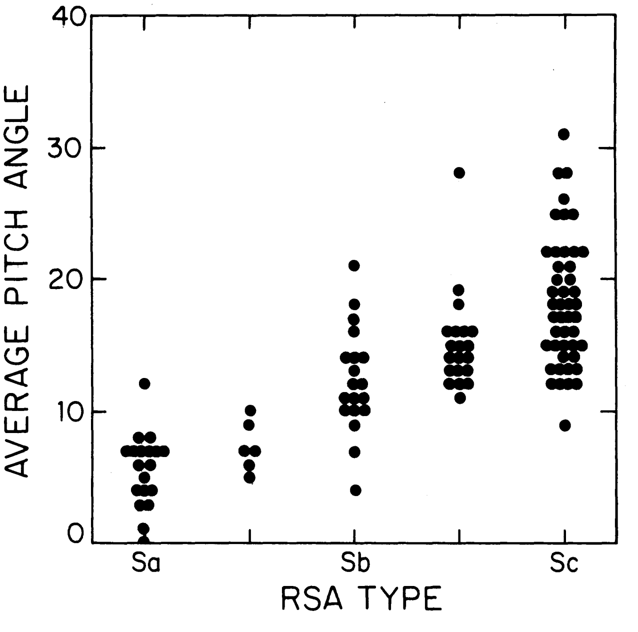

FIG. 7. Measured pitch angle vs Hubble type, the latter from Sandage and Tammann.

compared in Fig. 6. The rms difference is 2.6°, which is consistent with the measuring errors. A few galaxies are very discrepant, however, and deserve special comment. In virtually all cases the disagreements occurred for galaxies with short patchy arms (e.g., NGC 2403), and a closer examination of the modern photographic material and Danver's notes (1942) strongly suggests that Danver erred in connecting unrelated arm segments into single arms. His plate material usually consisted of first-generation emulsions exposed on small-scale telescopes, and traceable arms were often only revealed after an elaborate series of post-exposure contrast enhancement procedures (Danver 1942, Chap. 4). The present measurements confirm his results for nearby, strong-armed spirals. For the more distant, poorly resolved objects in his sample (including ~60 judged too patchy to be measured in modern material here), however, the results should be applied with more caution.

IV. ARM SHAPE AND THE HUBBLE SEQUENCE

a) Dependence on Hubble Type

The tightness of the spiral pattern, in addition to the disk resolution and bulge-to-disk ratio, are the fundamental criteria in Hubble's (1936) classification of spirals. In order to better understand the nature and origin of the sequence, and to better evaluate the different classifications which have recently been published, it is instructive to intercompare the three criteria within a common set of objects.

Figure 7 compares arm pitch as measured here with morphological type as determined by Sandage and Tammann in their *Revised Shapley-Ames Catalog* (RSA) (1981). The RSA classifications are based almost solely upon disk resolution (Sandage, private communication), and hence Fig. 7 is essentially a consistency test between two of Hubble's classification parameters.

The results confirm that there exists a smooth, monotonic increase in the openness of the spiral pattern with later Hubble type *on the average*, but that the variation in pitch among galaxies of a given type is very large. Schweizer (1975) noted a similar behavior in Danver's data. Part of this scatter can be attributed to the observed dispersion of arm pitch among the individual galaxies themselves, which introduces an average "uncertainty" of ± 2°–3° (± 1° for the early-type galaxies) to the individual points in Fig. 7. An additional dispersion of comparable magnitude is to be expectd from the discrete binning of the measured Hubble types. A large portion of the observed dispersion, however, must be real. In the extreme, NGC 5364, a textbook (Sandage 1961) Sc galaxy in terms of both disk resolution and bulge-to-disk morphology, possesses a well measured pitch angle which is typical of late Sa or early Sb galaxies. An inspection of Table III will reveal numerous other examples. These results guarantee that different Hubble classifications based on different weighting of arm morphology of disk resolution will lead to inconsistencies if the data sets are indiscriminately mixed. A discussion of this problem with regard to recent statistical studies of galaxy populations will be deferred to Sec. IV b.

Before proceeding it is worthwhile noting that the statistical results in Fig. 7 are very similar to those derived

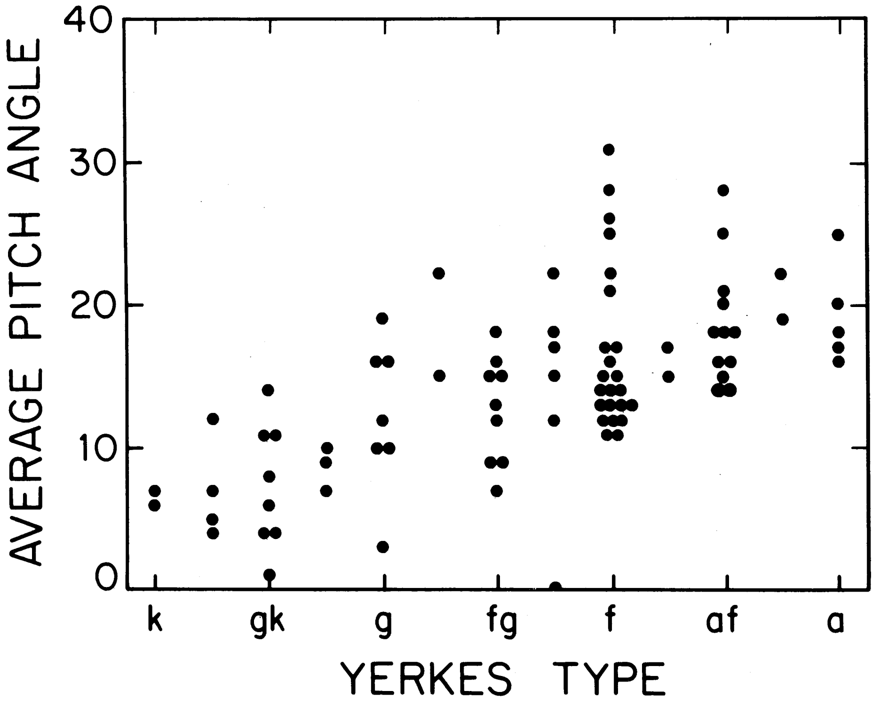

FIG. 8. Measured pitch angle vs the morphological classifications of Morgan. The latter emphasize disk/bulge morphology.

earlier by Danver (1942), for the Sb–Sc galaxies which he measured. (Virtually no earlier systems were measured by Danver.) Consequently the results of studies based on Danver's statistics are essentially unaffected by these results.

b) Dependence on Yerkes Type

A quantitative comparison of arm pitch with disk/bulge morphology is more difficult to make. Photometric disk-to-bulge ratios are only available for a handful of spirals (Boroson 1980). For the seven galaxies in common with the present sample, a plot of B/D vs arm pitch is a virtual scatter diagram. Given the small sample, however, the significance of this result is uncertain.

A larger sample of subjectively estimated bulge-to-disk ratios is available from Morgan's (1958, 1959) classifications. His Yerkes types are based solely on the central concentration of the galaxies, and are denoted using an analog of the stellar classification sequence, from a (early) to k (late), to reflect the dominant contributors to the blue light, and to distinguish the Yerkes types from the only partially correlated Hubble types. Figure 8 plots the pitch angles measured here as a function of Yerkes class, and shows again a smooth *average* dependence between bulge-to-disk morphology and arm shape, but with an even larger scatter than in Fig. 7. This large dispersion cannot be explained away as due to observational error alone. A large portion must be real. Finally, a comparison of Hubble and Yerkes types (de Vaucouleurs 1963) has demonstrated that those parameters are also only weakly correlated, independent of arm shape.

Taken together these results demonstrate that the Hubble sequence is not the idealized, one-dimensional sequence as it is often portrayed. Examples of galaxies with inconsistent classification criteria have been known for some time (e.g., Sandage 1961, 1975); here the problem is verified as a general phenomenon. A direct consequence is that statistical studies of galaxy properties which mix different sets of classifications may be led to serious systematic biases. Among the recent sets of classifications available include those in which all three criteria are considered (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), two for which disk texture is the primary criterion (Nilson 1973; Sandage and Tammann 1981), one in which disk-to-bulge is the primary discriminant (van den Bergh 1976), and a number for which disk/bulge and spiral arm morphology are primarily considered (Dressler 1980; Wilkerson 1980). The different systems may not be equivalent, and any differences may be strongly distance dependent. Biases may be particularly severe in studies of very heterogeneous samples of spirals, such as field versus rich cluster members, where there is virtually no overlap between the different classification data.

c) Luminosity Dependence and Sample Completeness

The present sample of galaxies is doubly undersampled for faint spirals. In addition to the volume effect, the ragged, irregular structure of the spiral arms in fainter spirals discriminates against their inclusion in

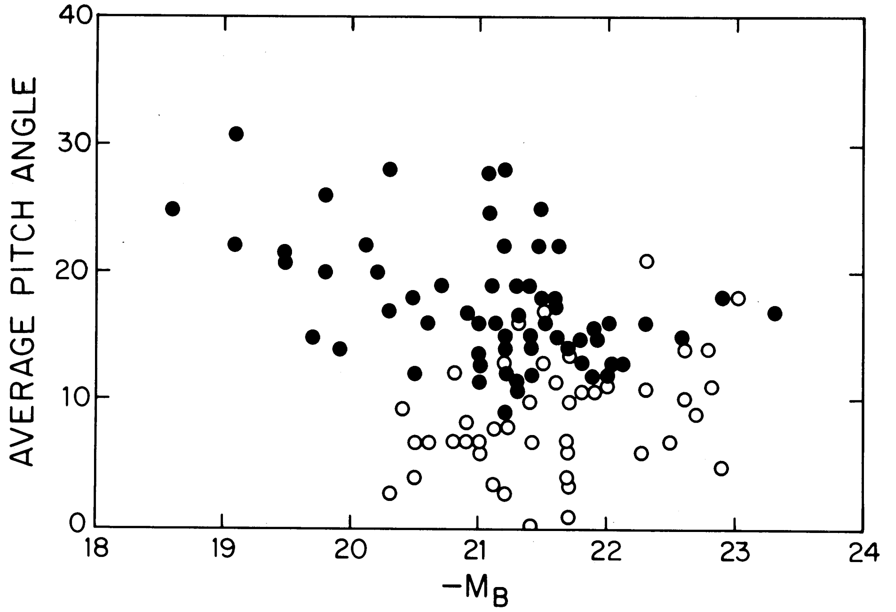

FIG. 9. Measured pitch angle of the spiral arms vs the approximate absolute blue magnitude of the parent galaxy, from Sandage and Tammann. Closed circles—Sbc and Sc galaxies; open circles—Sa–Sb.

this analysis. Consequently Figs. 7 and 8 should not be regarded as representing the precise, complete distributions of spiral arm morphologies among galaxies of a given type. To assess the bias, arm pitch is plotted as a function of galaxian blue luminosity in Fig. 9, for Sbc–Sc galaxies (closed circles) and for Sa–Sb spirals (crosses). Absolute magnitudes were taken directly from Sandage and Tammann (1981). A slight trend in arm shape with luminosity is apparent for the late-type spirals, although the large scatter indicates that the two properties are only very loosely associated. For the early spirals no such trend is apparent. Consequently it appears that Figs. 7 and 8 do offer a reasonable representation of the distribution of arm shapes along the Hubble sequence, except for the Sc galaxies where galaxies with large pitch angles (open arms) are somewhat underrepresented.

V. PHYSICAL BASIS

The question of the origin of the smooth trend in arm shape with type has given rise to attempts by both the density wave (Roberts, Roberts, and Shu 1975) and stochastic (Seiden and Gerola 1979) theory groups to explain the phenomenon within the contexts of their spiral structure pictures. An explicit comparison of observed and predicted arm shapes has appeared elsewhere (Kennicutt and Hodge 1982). Both sets of models agree crudely with the measured arm properties, but large systematic differences plague both as well. The linear

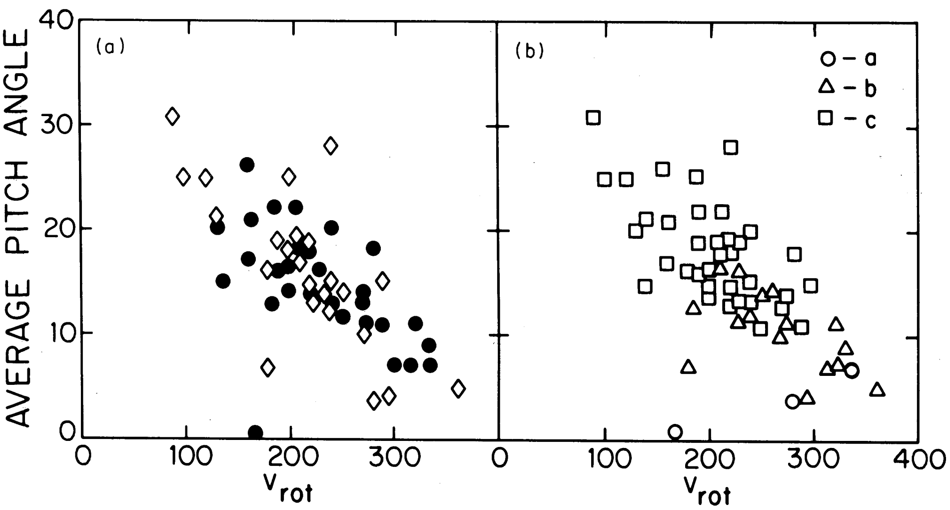

FIG. 10. Measured pitch angles vs the maximum rotation velocity. In (a) the results are separated by the source of velocity data, either published rotation curves (closed) or from integrated 21-cm H II profiles (open). In (b) the results are segregated by galaxy type.

WKB density wave spirals are invariably too tight, by about a factor of 2 in pitch, while the stochastic models agree only on the average, with a large uncorrelated scatter about the average. For details see Kennicutt and Hodge (1982).

The ability of two such radically different models to at least crudely reflect the trends in pitch with type suggests that perhaps the shapes of spiral arms are largely dictated by kinematic factors which will manifest themselves in any number of models for the origin of the arms (Kennicutt and Hodge 1982). This possibility has been explored in Fig. 10, in which arm pitch has been plotted as a function of the maximum rotational velocity of the galaxy. Two sets of velocities were used, velocities from published rotation curves (closed circles) and from integrated 21-cm H I line profiles (open circles). A fairly strong correlation is apparent, one in fact which is as good as the theoretical model comparisons in Kennicutt and Hodge (1982), suggesting that rotational velocity is a major determinant of arm shape, independent of the physical origin of the arms. Again, however, there is an observational scatter which can only be partially explained by observational uncertainties. NGC 6946, 4826, and 3185 all possess arms which lie 15° in pitch from the mean relation; errors in rotation velocity of ~ 200 km s^{-1} would be required to explain the discrepancy. Instead it seems almost certain that a second parameter is required in addition to rotation velocity to explain the change in pitch along the Hubble sequence. This empirical conclusion is congruent with the theoretical expectations of Roberts *et al.* (1976), in which it is argued that two parameters, possibly galaxian mass and central concentration, may dictate the arm shape. By the same token the results here are probably inconsistent with material arm pictures, in which the arm shape reflects the effects of differential rotation alone.

This latter point is emphasized in Fig. 11, which shows the average pitch angles plotted as a function of the mean angular rotation speed, estimated by dividing the maximum rotation velocity by the radius of the spiral pattern. Perhaps surprisingly, little or no correlation is apparent. Differential rotation is apparently not the primary determinant of arm shape, but rotation velocity may be. It is also interesting to note that the same conclusion appears to apply within a given spiral pattern. As seen earlier the pitch angle in a well developed spiral remains relatively constant with radius (on the average). The recent work on rotation curves by Rubin, Ford, and others suggests that over most of this region it is the rotation velocity which is constant (i.e., flat rotation curve), while the angular rotation v/r monotonically decreases.

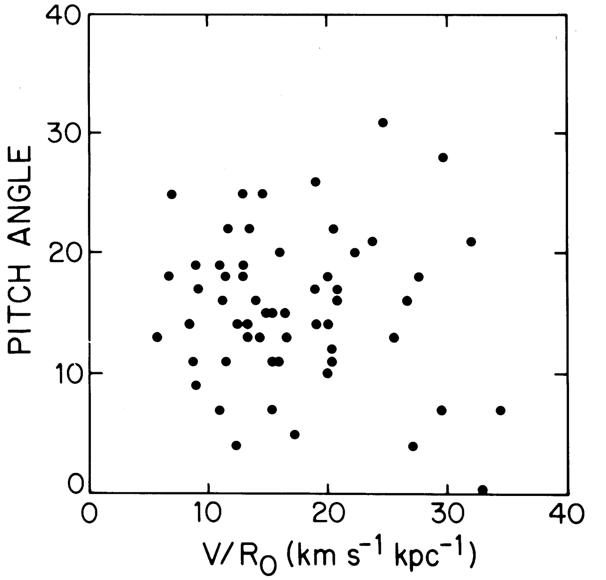

FIG. 11. Average measured pitch angle vs the angular rotation velocity as defined in the text.

While the data presented here strongly suggest that a second kinematic parameter in addition to V_{max} is required to explain the morphology of the spiral pattern, they do not offer any evidence (at least to me) of what that second parameter might be. Figure 10(b) shows the data in Fig. 10(a) broken down by Sandage-Tammann (1981) type, with Sab and Sbc galaxies plotted as Sb and Sc, respectively. The early spirals are segregated with respect to both arm shape and V_{max}, with no clear evidence of a second parameter. Other comparisons with Yerkes type, etc., are similarly inconclusive. Far more valuable would be quantitative information on the structure and kinematics of the individual galaxies, so that the effects, for example, of mass and mass concentration could be separated.

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