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EVIDENCE FOR SMALL HALOS IN GRAND DESIGN SPIRAL GALAXIES

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ABSTRACT

A comparison of 41 rotation curves suggests that grand design galaxies tend to have falling rotation curves between $0.8R_{25}$ and $1.2R_{25}$, while flocculent and multiple arm galaxies have nearly flat or rising rotation curves in this range. This observation is consistent with the theoretical prediction that long spiral arms require a high fraction of the total galaxy mass to be in the form of a cool disk population. The correlation also implies that spiral morphology is a semipermanent feature of a galaxy disk, like the rotation curve. In that case, isolated nonbarred flocculent galaxies probably cannot amplify $m = 2$ wavemodes from internal perturbations, so these galaxies are usually flocculent, whereas isolated nonbarred grand design galaxies can amplify such modes, so they are usually grand design. Interacting grand design galaxies with falling rotation curves, such as M51 and M81, may have had long spiral arms or global modes before their interactions, because there was always a strong amplifier for *internal* perturbations. The current spirals in these galaxies differ only because they result from the amplification of recent *external* perturbations.

Subject headings: galaxies: internal motions — galaxies: structure

I. INTRODUCTION

The theory of galactic spiral waves predicts that noninteracting galaxies with long spiral arms should have a large fraction of their total mass in the disk, and that galaxies with numerous short arms or no spiral waves should have a large fraction of their total mass in the halo (Bertin *et al.* 1977; Lau and Bertin 1978; Toomre 1981; Athanassoula 1984; Sellwood and Carlberg 1984; Carlberg and Freedman 1985). If this prediction were confirmed and calibrated by direct observations, then the spiral structure of a galaxy could be used as an indicator of the unseen halo mass (e.g., Athanassoula, Bosma, and Papaioannou 1987).

The purpose of this paper is to compare the rotation curves of galaxies with various types of spirals, concentrating primarily on the outer parts of the rotation curves, near the edges of the optical disks.

II. ROTATION CURVE ANALYSIS

The outer rotation curves of 41 galaxies were examined from all of the available published data. As in Whitmore *et al.* (1988), we define the extended gradient (EG) of a rotation curve as the percent difference between the velocities at $1.2R_{25}$ and $0.8R_{25}$, divided by the maximum rotation velocity

$$EG = \frac{v(1.2R_{25}) - v(0.8R_{25})}{v_{\max}} ,$$

where R_{25} is the radius at which the surface brightness is 25 mag arcsec^{-2}.

The extended gradients for all galaxies with both published outer rotation curves and suitable inclinations and sizes for examination of the spiral structure are tabulated in Table 1 and plotted as a function of spiral arm class in Figure 1. The A symbols in the figure represent spiral types SA, the B symbols represent types SB, and the X symbols represent types SAB, from de Vaucouleurs, de Vaucouleurs, and Corwin (1976). Twenty-two of the EGs are from Whitmore *et al.* (1988); the other 19 were determined from the H I rotation curves referenced in the table.

The spiral arm classes in the figure are designated flocculent (F), multiple arm (M), and grand design (G). For most of the galaxies in this study, the arm classes come from the catalog in Elmegreen and Elmegreen (1987). For the present paper, we take arm classes 1 through 4 to be type F, arm classes 5 through 9 to be type M, and arm class 12 to be type G. Three of the galaxies included here from Whitmore *et al.* (1988) were too small to be classified in our catalog, so their arm types were determined from photographs in Rubin *et al.* (1988).

Although the galaxy sample is small at the present time, Figure 1 indicates that flocculent and multiple arm galaxies have larger extended gradients than grand design galaxies, which tend to have falling rotation curves in their outer parts (negative EG). The average values of EG, expressed as percentages with standard deviations, are 2.9 ± 9.5 (type F, 15 galaxies), 1.0 ± 7.1 (type M, 21 galaxies), and -11.6 ± 8.5 (type G, 5 galaxies). These averages are connected by a dashed line in the Figure (they do not include M51, discussed below). The dotted line separates positive from negative extended gradients.

Several galaxies have slowly falling rotation curves *inside* R_{25} with no available velocity data beyond. These are not included here because the rotation curve could level off or begin to rise again beyond R_{25}, which is the case for UGC 4329, a flocculent galaxy in Whitmore *et al.* (1988). We make an exception for the grand design galaxy M51, however, and plot it in Figure 1, because its rotation velocity has an unusually rapid decline between $0.55R_{25}$ and $0.9R_{25}$, which is the last measured point in Tully (1974). For the plotted value of EG, we take $[v(0.95R_{25}) - v(0.55R_{25})]/v_{\max}$ because the radial range is the same as in the definition of EG above.

Some of the F or M type galaxies in Table 1 have rising or

TABLE 1

Galaxies with Arm Classes and Extended Rotation Curves

NGC	Arm Class	Extended Gradient	Reference[a]
247	2[b]	14	WFR
253	5	0	P
300	5	1	WFR
598	5	0	H
925	1	2	W
2403	4	5	WFR
2841	3	−6	WFR
2903	7	−1	WFR
3031	12	−9	WFR
3109	1[b]	14	WFR
3198	9[b]	−2	WFR
3359	5	12	G
3521	3	−2	CG
3726	5	−4	W
3898	3	0	RBFT
3992	9	−11	G2
4151	5	7	B
4236	2[b]	9	WFR
4242	1	4	W
4254	9	14	WFR
4258	9[b]	4	WFR
4303	9	1	WFR
4321	12	−28	WFR
4395	1	11	W
4501	9	6	WFR
4535	9	18	WFR
4725	6	−9	W
4736	3	−24	WFR
5033	9	3	WFR
5055	3	−6	WFR
5236	9	−6	B
5371	9	−1	W
5383	12	−5	B
5457	9	−6	H
6946	9	−5	RSR
7331	3	4	B
7591	12	−11	WFR
7631	4	8	WFR
UGC 4329	2	11	WFR
DC 39	12	−5	WFR
IC 342	9	1	B

[a] WFR = Whitmore, Forbes, and Rubin 1988; H = Huchtmeier 1975; W = Wevers 1984; B = Bosma 1978; G = Gottesman 1982; G2 = Gottesman 1985; P = Pence 1981; RBFT = Rubin *et al.* 1985; RSR = Rogstad, Shostak, and Rots 1973; CG = Casertano and van Gorkom 1990.

[b] Indicates uncertain arm classes.

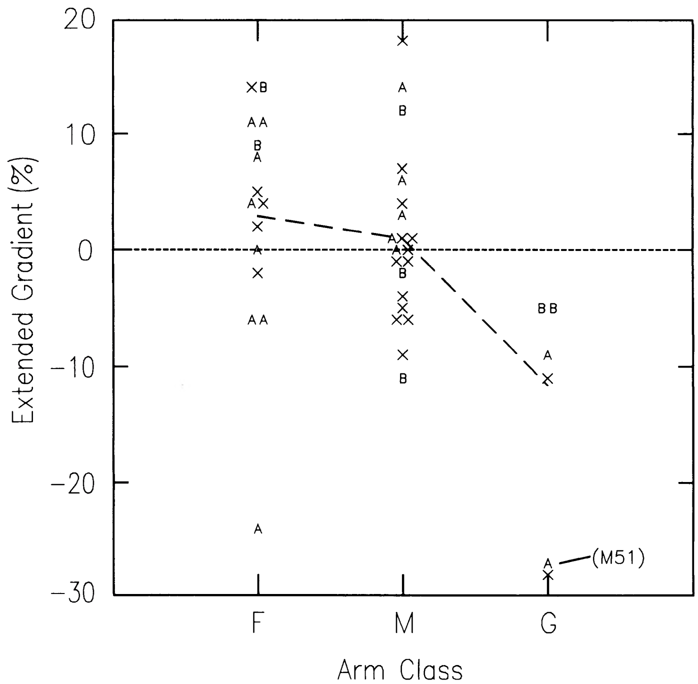

Fig. 1.—The (percent) extended gradient in the rotation curve is shown as a function of the spiral arm type, where F, M, and G represent flocculent, multiple arm, and grand design galaxies. Symbols represent spiral types A (nonbarred), X = AB (oval), and B (barred). The position of M51 is also indicated; the plotted gradient for M51 comes from the radial range $0.55R_{25}$–$0.95R_{25}$, instead of the range $0.8R_{25}$–$1.2R_{25}$, as for the other galaxies.

flat rotation curves in the range $0.8R_{25}$–$1.2R_{25}$, but falling rotation curves beyond this. Other galaxies in the compilation by Casertano and van Gorkom (1990), particularly the early Hubble types, also have negative gradients beyond $1.2R_{25}$. These falling rotation curve segments indicate that the halo begins to terminate somewhere beyond $1.2R_{25}$, but this conclusion is probably not relevant to the present study, since the stellar spiral structure generally lies inside R_{25}. We presume that when the rotation curve begins to fall somewhere beyond $1.2R_{25}$, the main part of the optical disk responds to a spiral perturbation as if the halo were still relatively massive there.

III. DISCUSSION

A falling rotation curve in the radial range $0.8R_{25}$–$1.2R_{25}$ is evidence that a large fraction of the total galaxy mass is in the visible portion of the disk. It implies that the disk is massive in a dynamical sense, and that the WASER and swing-amplifier mechanisms for galactic density waves should be strong (Mark 1976; Toomre 1981; Lin 1983). Moreover, the falling rotation curve itself can promote spiral instabilities, regardless of the disk/halo mass ratio, because the resulting value of the instability parameter J will be large when shear is large (Lau and Bertin 1978). Thus, the symmetric spirals in many grand design galaxies may be the result of strong amplification of internal or external perturbations, with the large strength of the amplification resulting from a relatively massive disk.

This conclusion could be proven wrong by the observation of an isolated, nonbarred G galaxy with a flat or rising rotation curve in the radial range 0.8–$1.2R_{25}$, i.e., close to the outer Lindblad resonance, where the spiral ends. The observation of an F or M galaxy with a negative extended gradient (e.g., NGC 4736) does not contradict the conclusion because grand design spirals probably require other conditions, too, such as a shielded inner Lindblad resonance or no inner Lindblad resonance, or a small bar or oval in the center so the wave can reflect or refract off the inner regions. The relative gas mass in the disk might also have to be large for a grand design spiral (see, for example, the computer simulation in Thomasson *et al.* 1990). The observation of a barred or interacting grand design galaxy with a positive extended gradient does not contradict the conclusion either, because strong perturbations like bars and companions can presumably create grand design spirals even with weak amplification in a low-mass disk.

Figure 1 also suggests that even though F and M galaxies *can* have negative extended gradients (in which case they lack the G structure for some other reason) and G galaxies with bars or companions can have positive extended gradients (in which case the G structure would be driven in a weakly responding disk by a strong perturbation), the F and M galaxies *usually* have only small or positive extended gradients, and the G galaxies, even with bars, usually have only negative extended gradients. That is, there is nearly a one-to-one correspondence between spiral arm morphology and extended gradient. If this correlation persists in a larger sample, then it implies that spiral arm morphology is a semipermanent feature of a galaxy disk, like the rotation curve. In that case, flocculent or multiple arm galaxies with positive EGs may rarely have a symmetric grand design structure because they *cannot* easily support $m = 2$ wave modes. If a strong interaction triggers an $m = 2$ spiral in such a galaxy, then it will not stimulate a wave mode but only a tidal wave which amplifies a little and then wraps up and disappears (as in Toomre 1981). On the other hand, grand design galaxies with negative extended gradients may commonly have such symmetric spirals. If one particular modal oscillation grows too strong and breaks apart, then it will probably be replaced by another one (as long as the stellar disk remains cool).

The correlation implied by Figure 1 also suggests that galaxy interactions may sometimes trigger grand design structures in disks that are already close to the threshold for forming such structures independently. Such galaxies could have had an $m = 2$ mode before the interaction and a different $m = 2$ mode after the interaction. The rotation curve in M51, for example, is sharply falling in the outer part, so this galaxy may be *intrinsically* similar to the other grand design galaxies in Table 1, although the others do not have such obvious companions as NGC 5195. The grand design galaxies M81 (Table 1) and, possibly, NGC 7753 (Marcelin *et al.* 1987) also have falling rotation curves, so recent interactions with the companions M82 and NGC 7752 may have restarted wave modes that were already present but formerly at a different phase. Galaxies with massive disks might also be more likely to form bars during an interaction than galaxies with low mass disks (Gerin, Combes, and Athanassoula 1990).

The similarity between the F and M rotation curves, and the difference between these and the G galaxy rotation curves, although in approximate agreement with expectations from theory, is still somewhat puzzling in detail. Theoretical analyses and computer simulations suggest that any isolated galaxy with long arms, including *both* M and G types, should have a relatively large disk mass to amplify the spirals. The difference between M and G types in these models results from a difference in the number of modes that can be excited, which depends on other galaxy properties such as the amount of gas and dissipation in the waves or the presence of an inner reflecting or refracting barrier. Thus, we would have expected both the M and G galaxies to have falling outer rotation curves and only the F galaxies to have flat or rising curves. Perhaps this discrepancy will be resolved with a larger sample of galaxies or a refinement of the theory.

IV. CONCLUSION

Galaxies with two long and symmetric arms tend to have falling outer rotation curves, and galaxies with long multiple arms or short flocculent arms tend to have nearly flat or rising rotation curves near the edges of the optical disks. This observation suggests that galaxies with fundamentally different spiral arm morphologies also have different relative disk masses, with grand design galaxies having the largest disk to halo mass ratio.

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