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PROPERTIES OF SPURS IN SPIRAL GALAXIES

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ABSTRACT

Spiral arm spurs were analyzed on *B* and *I* photographs of NGC 628, NGC 2403, NGC 3031, NGC 4321, NGC 5194, NGC 5236, and NGC 5457. The inclination-corrected pitch angles, lengths, and widths of the spurs, and separations between adjacent parallel spurs, were measured. Time scales for significant shearing of the spurs due to differential rotation and to spiral density waves were determined from published rotation curves. Spurs appear to be long-lived features with pitch angles of about 60° and widths of some 560 pc.

Subject headings: galaxies: structure

I. INTRODUCTION

Late-type spiral galaxies are characterized by multiple spiral arms (Sandage 1961). Typically there are two main inner spiral arms that fragment and branch into many arms which comprise the overall spiral structure. Often in addition to these long, continuous branches there are other segments, called "spurs," which jut out from spiral arms (Weaver 1970*a*). They do not add to the regular spiral pattern, but end abruptly. They may be as wide as a spiral arm, but they extend at most from one arm to the next, and they cannot be traced back to the nucleus. It is common to find two or more spurs which are close together and parallel to one another, as in NGC 628 (Fig. 1, Pl. 12).

A study of dust lane widths and of dark "feathers" that cut across spiral arms was made by Lynds (1970). Piddington (1973) noted that the feathers and interarm bridges (spurs) often are seen in combination, as if they are a single type of feature. Dust lanes also may bifurcate and be parallel to a spur, as in M51.

Sometimes H II regions form chains which are not in the spiral arms but are parallel to them, as in NGC 3310 (van der Kruit and de Bruyn 1976); in some galaxies, such as NGC 7793, a string of H II regions may be parallel to spurs (Elmegreen 1979).

Our own Galaxy has spurs (Weaver 1970*a*, *b*; Herbst and Assousa 1978). Included in one spur is the intense star-forming region in Orion. For the purposes of distinguishing between large-scale and local by-products of spiral structure, as well as for understanding where stars may be formed, it is important to investigate the common properties of spurs.

In this paper we have selected seven spiral galaxies which exhibit spurs and pairs of spurs. The widths, lengths, and pitch angles of the spurs, and separation between adjacent spurs, were measured. These properties are interpreted within the context of rotation curves and of theories for the formation of spiral structure.

II. OBSERVATIONS

The galaxies selected for analysis of spurs were NGC 628 (M74), NGC 2403, NGC 3031 (M81), NGC 4321 (M100), NGC 5194 (M51), NGC 5236 (M83), and NGC 5457 (M101). Their classifications (given by de Vaucouleurs, de Vaucouleurs, and Corwin 1976) are listed in Table 1. These galaxies were chosen from the lists of galaxies with measured rotation curves, summarized by van der Kruit and Allen (1978), Kormendy and Norman (1979), and Rubin, Ford, and Thonnard (1980). The majority of the galaxies in these surveys were eliminated from the present analysis because they were too highly inclined to the line of sight ($i \gtrsim 60°$) to allow discrimination between spurs and the ends of spiral arms. Several more galaxies were not considered because they were too early in type or too irregular to exhibit spiral arm spurs. However, a glance through a catalog such as the Hubble Atlas (Sandage 1961) reveals that spurs are common features in most late-type spirals. The spiral galaxies studied here are also convenient because they are close enough to allow good resolution of their features.

Blue and near-infrared exposures were used in the analysis. *B* plates (baked 103a-O emulsions with GG385 filter, $\lambda_{\rm eff} \approx 4400$ Å) and *I* plates (hypersensitized IV-N emulsions with Wr 88A filter, $\lambda_{\rm eff} \approx 8250$ Å) were taken on the Palomar 1.2 m Schmidt telescope in 1978 April and 1980 March. Plates for NGC 628 were taken on the CTIO[2] 4 m telescope in 1978 September. Published high-resolution photographs of these galaxies (e.g., Sandage 1961) also were examined. Figures 1 and 2 (Plates 12, 13) show two representative galaxies with spurs, NGC 628

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TABLE 1

SELECTED GALAXIES AND THEIR SPURS

Galaxy	Type	Distance (Mpc)	Inclination (degrees)	Spur	R_1 (kpc)	Width (pc)	Length (kpc)	Pitch Angle (degrees)
NGC 628 (M74)	SA(s)c	18.2	4	1	3.4	810	3.7	77
				2	8.1	660	2.8	66
				3	8.9	570	3.4	80
				4	9.2	740	3.0	48
				5	12.6	740	4.8	46
NGC 2403	SAB(s)cd	3.25	54	1	2.0	200	0.80	56
				2	2.0	200	0.85	55
NGC 3031 (M81)	SA(s)ab	3.25	55	1	4.5	540	1.8	54
				2	4.6	410	1.7	44
NGC 4321 (M100)	SAB(s)bc	20.0	35	1	4.9	1280	2.8	71
				2	5.5	980	2.2	72
				3	6.0	200	1.4	53
NGC 5194 (M51)	SA(s)bcp	9.6	35	1	5.6	340	2.9	65
				2	6.1	500	2.8	61
				3	6.6	270	2.5	48
				4	7.5	680	1.6	66
				5	8.3	650	0.64	76
				6	8.6	470	0.84	80
NGC 5236 (M83)	SAB(s)c	8.9	13	1	4.6	310	2.5	63
				2	5.3	430	1.3	77
				3	7.5	300	2.2	60
				4	7.6	930	2.5	63
				5	8.9	340	1.9	33
NGC 5457 (M101)	SAB(rs)cd	7.2	22	1	5.0	650	3.5	74
				2	5.3	700	3.1	60
				3	8.7	680	4.1	64
				4	10.7	580	3.7	68
				5	11.9	640	3.1	72

and NGC 3031. In Figure 1 are ultraviolet and near-infrared photographs of NGC 628, and in Figure 2 are blue and near-infrared photographs of NGC 3031. The spurs studied in this analysis are labeled by numbers.

The well-defined and prominent spurs were identified in each galaxy in this study and are listed in Table 1. This sample of spurs seems to be representative of all prominent spurs, based on inspections of plates of other galaxies.

For each galaxy in Table 1, information about spurs was corrected for projection effects by tracing the spurs on a diagram of concentric ellipses which were oriented along the galaxy position angle. The ellipticities were determined from the inclinations of the galaxies. In this way the position and orientation of each spur in a particular galaxy was taken into account in making the inclination corrections. In Table 1 the corrected lengths, widths, and pitch angles (angle between the spur and a circle at the same radius as the starting point of the spur) of the 28 measured spurs are recorded. The estimated measuring error is $\pm 5°$ for the pitch angles. Uncertainties in defining precise edges of the spurs lead to errors of ± 100 pc in measuring the widths and lengths.

III. SHEARING TIME SCALES

a) Individual Spurs

Having measured the basic properties of these spurs, we may use the published rotation-curve properties of each galaxy to derive time scales during which the features may be expected to change their appearance significantly. Several different time scales may be applicable depending upon the overall dynamics taking place in a particular galaxy. The first time scale we will consider measures how long it would take for an existing spur to be sheared by the differential rotation of the galaxy. The effect of this shearing would be to change the pitch angle of the spur by a factor of ~ 2. We have:

$$t_{\text{diff rot}} = \frac{R_1 \Delta\theta_{12}}{R_1 \Omega(R_1) - R_2 \Omega(R_2)}, \qquad (1)$$

where $\Delta\theta_{12}$ is the projection-corrected angle difference in radians between the spur endpoints, $\Omega(R_1)$ and $\Omega(R_2)$ are the inclination-corrected angular velocities at each end of the spur, and R_1 and R_2 are the galactocentric radii of the endpoints which are nearest and farthest from the nucleus, respectively. References for the angular velocities used in this analysis are as follows: NGC 628, Briggs *et al.* (1980); NGC 3031, Rots (1975); NGC 4321, van der Kruit (1973); NGC 5236, Rogstad, Lockhart, and Wright (1979); NGC 2403, 5194, and 5457, Jensen, Strom, and Strom (1976).

Another time scale may be useful if there is an underlying density wave ordering the overall spiral structure in a galaxy. This second time scale is inversely proportional to the gas speed relative to a spiral–density-wave-pattern speed:

$$t_{\text{SDW}} = \frac{R_1 \Delta\theta_{12}}{R_1[\Omega(R_1) - \Omega_p] - R_2[\Omega(R_2) - \Omega_p]}. \qquad (2)$$

TABLE 2

SPUR TIME SCALES

Galaxy	Pattern Speed ($km\ s^{-1}\ kpc^{-1}$)	Spur	$t_{diff\ rot}$ ($\times 10^8$ yr)	t_{SDW} ($\times 10^8$ yr)	Adjacent Spurs	Separation (kpc)	t_{separ} ($\times 10^7$ yr)
NGC 628	8.7	1	0.23	0.12			
		2	1.6	0.38	2, 4	7.7	9.7
		3	1.4	0.18	3, 4	5.6	7.4
		4	5.5	0.84			
		5	46.0	1.10			
NGC 2403	26.0	1	0.32	1.00	1, 2	0.5	1.3
		2	0.33	1.20			
NGC 3031	20.0	1	2.1	0.65	1, 2	1.7	1.1
		2	2.5	0.41			
NGC 4321	9.6	1	0.092	0.073	1, 2	2.8	2.7
		2	0.13	0.09			
		3	0.26	0.19	1, 3	10.5	10.0
NGC 5194	14.4	1	4.4	0.33	1, 2	1.3	1.7
		2	3.5	0.42	2, 3	1.8	3.3
		3	6.6	0.68			
		4	1.6	0.25	4, 5	2.6	4.7
		5	0.65	0.14	5, 6	1.4	2.8
		6	2.9	0.13			
NGC 5236	18.9	1	3.0	2.10	1, 2	5.3	1.9
		2	0.16	0.47			
		3	0.59	0.65	3, 4	3.4	3.4
		4	0.37	0.33			
		5	2.9	0.13			
NGC 5457	12.0	1	0.22	4.30	1, 2	5.6	7.9
		2	0.41	2.80			
		3	0.48	2.40	3, 4	2.8	5.4
		4	7.1	0.34	4, 5	2.1	5.9
		5	2.6	0.25			

For NGC 2403, NGC 5194, and NGC 5457, the values of the angular velocities $\Omega(R)$ minus the pattern speeds Ω_p were taken from Jensen, Strom, and Strom (1976). For the remaining galaxies, the original rotation curves were used. In these latter cases, the pattern speed was estimated by the method of Roberts, Roberts, and Shu (1975): the position of the outermost visible H II region was taken to be the radius of corotation, where $\Omega_p = \Omega(R)$. The values of Ω_p which were used in this analysis are listed in Table 2.

b) Adjacent Spurs

The relationship between different spurs in the same galaxy also was considered. In each case where two or more nearly parallel spurs started at about the same galactocentric radius, the separation between adjacent spurs was measured at the average of the midpoints of the two spurs. The arcs of separation were corrected for inclination and converted to linear values by applying the distances to each galaxy (Table 1), and the results are recorded in Table 2.

The separations between adjacent spurs may be used to get a time scale based on the passage of a spiral density wave. In analogy with equation (2), we get:

$$t_{separ} = \frac{D}{R[\Omega(R) - \Omega_p]}, \tag{3}$$

where D is the average linear separation between two adjacent spurs, and R is the average galactocentric radius of the spurs.

The results of all of the time-scale measurements are listed in Table 2.

IV. DISCUSSION

The widths of the spurs, averaging 560 pc $\pm$ 260 pc, are typical of the widths of spiral arms. The measured pitch angles of the spurs have an average value of $63° \pm 12°$, which is roughly 50° more than the pitch angles of the arms. The spurs always appear on the outer edges of spiral arms, and in no case is a spur pitch angle less than that of an arm. This result is comparable to the mean value for the pitch angles of dark feathers measured by Lynds (1970). The similarity in pitch angles lends support to the idea that spurs and dark feathers share a common origin. Some spurlike features were not included in this analysis because they could not be outlined easily; their edges are fuzzy. Nevertheless, they have pitch angles similar to those of the prominent spurs.

The time scales derived for the spurs are both relatively short compared with the galaxy lifetimes: $t_{diff\ rot} = 3.4 \pm 8.6 \times 10^8$ yr, and $t_{SDW} = 8.2 \pm 9.8 \times 10^7$ yr. These time scales indicate how long a spur may remain in its present configuration with a given pitch angle. Evidently in about 10^8 yr a material spur would change its pitch angle by roughly a factor of 2. Yet the small standard deviation in the measured spur pitch angles from galaxy to galaxy suggests that the pitch angles have remained fairly constant and that the spurs have not undergone much shearing; otherwise we might have expected to see a large standard deviation for the pitch angles of the different spurs in all of the galaxies. We do not feel that the observed sample was biased in favor of high-pitch-angle spurs; the only selection criterion was that the spurs be prominent features. They are readily distinguished in galaxies, as a glance at Figure 1 or 2 will confirm.

The short shearing time scales might be interpreted as an indication that spurs are very young and transient features. However, the spurs appear not only in blue photographs, but in the near-infrared photographs as well (see Figs. 1 and 2; also Elmegreen 1980*b*). The *B* passband emphasizes the light emitted by young stars and star-forming regions, with ages on the order of 10^7 yr. Spiral arms and spurs appear patchy in the *B* because they are dotted with H II regions. While star-forming regions or young stars which are highly prominent in the *B* also are evident in the *I*, the near-infrared picture of spurs and arms is much smoother than the blue (see Zwicky 1955; Schweizer 1976; Elmegreen 1979, 1980*b*). Schweizer (1976) showed that the *I* passband is most sensitive to light from older (perhaps disk) stars, with lifetimes of some 10^8–10^9 yr, with the contribution from young stars being only a few percent. The fact that we see spurs as well as arms in the *I* suggests that spurs are as long-lived as spiral arms.

This result implies that spurs are not the product of material movement, but occur because of a wave phenomenon. Furthermore, the separation between adjacent spurs varies from 0.5 to 10.5 kpc from one galaxy to another, and yet the average separation time scale based on a density wave (eq. [3]) has a small standard deviation: $t_{\text{separ}} = 4.6 \pm 3.0 \times 10^7$ yr. This also points to a large-scale wave process of formation, rather than to random localized events.

A detailed analysis of dust lanes and dust complexes in late-type spiral galaxies revealed that the dust opacity in dust lanes which followed branches (or spurs) was greater than the opacity in dust lanes which were adjacent to the main spiral arms (Elmegreen 1980*a*). The implied relative compression factors were measured to be proportional to the squares of the sines of the pitch angles of the dust lanes, as would be expected in density wave theory. Since spurs and their associated dust lanes most likely are formed by the same process, this result may be taken as further support for a wave origin of the spurs.

The nonlinear effects of gaseous flows in spiral–density-wave theory might allow for the generation of spurs. Mayor (1975) suggested that the local Orion "arm" is not a material feature, but a density wave by-product, and mentioned that Julian and Toomre (1966) could reproduce its pitch angle by imposing a spiral density "wavelet." Shu, Milione, and Roberts (1973) suggested that ultraharmonic resonances of higher modes of density waves might produce spurs and feathers. Pikelner (1970) theorized that feathers are the result of shocking as clouds pass through spiral arms, but his premise that clouds are ballistic objects may not apply (B. Elmegreen 1981). Mishurov and Suchkov (1976), on the other hand, consider a density wave with two disks rotating at different rates. Their interaction can produce conditions that are appropriate for spur formation.

However, the stochastic spiral arm model of Gerola and Seiden (1978), which depends on differential rotation, also is capable of reproducing short branches and spurs reminiscent of those observed in real galaxies. While the individual features in their model galaxies change with time, any given feature appears to last for one or more galactic rotation periods. The pitch angles of their spur-like features are greater than the spiral-arm pitch angles, and some stages in their evolutionary models show adjacent and roughly parallel spurs. These results seem to be consistent with the observations of the spurs presented here.

In summary, we conclude that spurs appear to be common and persistent features with long lifetimes comparable to those of spiral arms. The pitch angles and widths of the spurs are remarkably uniform from one galaxy to the next. The time scales which are based on the separations of adjacent pairs also have a small standard deviation. While a large-scale process such as a density wave is likely to have induced their formation, a local stochastic process cannot be ruled out.

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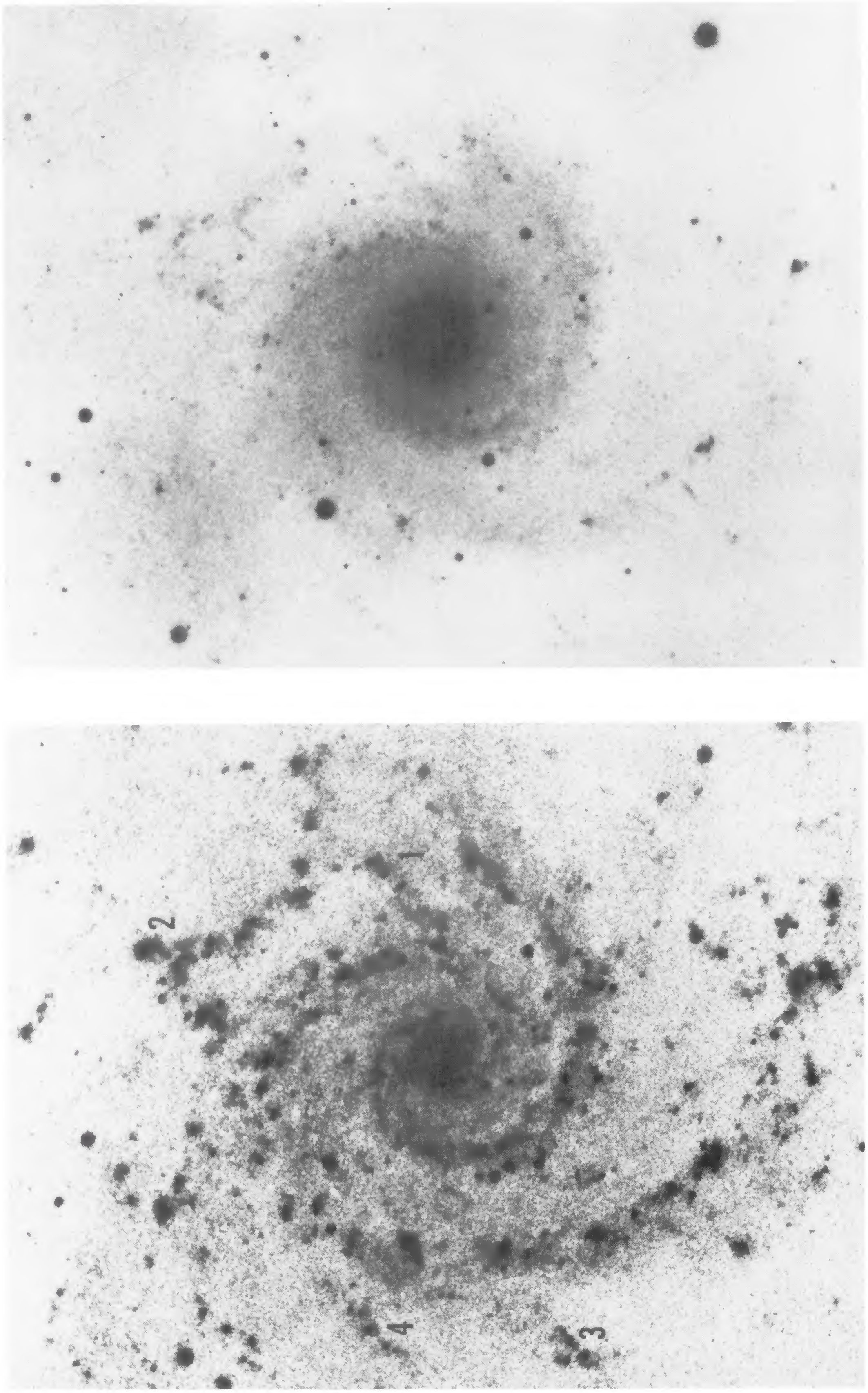

FIG. 1.—Photographs of NGC 628 taken on the CTIO 4 m telescope. (*a*) *U* plate (IIa-O + UG2, 60^m), with spurs numbered. (*b*) *I* plate (hypersensitized IV-N + RG695, 120^m)

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