H I OBSERVATIONS OF THE SPIRAL ARM PATTERNSPEED IN THE LATE-TYPE BARRED GALAXY NGC 925

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ABSTRACT

H I observations with the VLA of the late-type barred galaxy NGC 925 show clear streaming motions along four spiral arms close to the minor axis. A transition from inward streaming to outward streaming is found, presumably marking the corotation resonance. The realm of inward streaming extends to very large radii, corresponding to 1.2R₂₅ and 3 bar radii deprojected. This implies that most of the visible disk is inside corotation, although the H I disk extends beyond, at least to 2.5R₂₅. As a result, either the bar and the spirals are rotating separately or the bar rotates very slowly compared with early-type bars. There is apparently no inner Lindblad resonance because of the slowly rising inner rotation curve, and there may be no outer Lindblad resonance if the disk ends first.

Subject headings: galaxies: individual (NGC 925) — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: spiral — radio lines: galaxies

1. INTRODUCTION

NGC 925 is a late-type barred galaxy with de Vaucouleurs class SABd (de Vaucouleurs et al. 1991, hereafter RC3 [Third Reference Catalog of Bright Galaxies]), large optical diameter, D₂₅ = 10.47 (RC3), small distance, 9.3 Mpc (Silberman et al. 1996), and intermediate inclination, i = 55°8 (RC3). It has a bright optical bar of length 4' and two bright, patchy spiral arms beginning at the ends of the bar and extending out to ~3' (deprojected) along the minor axis where they seem to end. It also has H I spiral arms coincident with the optical arms but extending to about twice the radius. The fortuitous positioning of the optical and radio arms on the minor axis half way out in the disk, combined with the large size and favorable inclination, makes NGC 925 a good candidate for the observation of radial streaming motions along the arms, and for the possible determination of corotation where the radial streaming motions change sign.

NGC 925 is important for a study of pattern speeds because it has a late Hubble type and most determinations of pattern speeds are for earlier types (see review in Elmegreen 1996a). Early- and late-type bars have different lengths relative to the galaxy sizes and the rising parts of the rotation curves, and they have different luminosity profiles (Elmegreen & Elmegreen 1985; see review in Elmegreen 1996b). These differences led to the suggestion that early- and late-type barred galaxies have different pattern speeds, with corotation near the end of the bar in early types and farther out in late types (Elmegreen & Elmegreen 1985). Computer simulations have obtained this result too (Combes & Elmegreen 1993; Noguchi 1996).

The distinction between early- and late-type galaxies in this sense appears at a Hubble type of about SBBc (Elmegreen 1996b). Sempere, Combes, & Casoli (1995a) have in fact found a slowly rotating pattern for a barred galaxy of this transition type, NGC 7479, where corotation is at the edge of the optical disk, at ~3 bar lengths. NGC 4321 (SABbc) also has spiral arm corotation well beyond the bar, at ~1.8 bar lengths (Garcia-Burillo, Sempere, & Combes 1994; Sempere et al. 1995b).

However, corotation for galaxies as late in type as NGC 925 (SABd) have not been observed previously.

NGC 925 was observed with the VLA C configuration in 1996 April. A detailed discussion of the observations and the overall H I distribution are in Pisano, Wilcots, & Elmegreen (1997). Previous H I observations were reported by Gottesman (1980) and Wevers, van der Kruit, & Allen (1986). In what follows, we discuss the streaming motions in the arms and the implications for the pattern speed of the spiral.

2. STREAMING MOTIONS AND COROTATION

Figure 1 shows the H I column density map as a gray scale and the H I velocities as contours. The receding side is west, and north is up. For trailing spirals, this implies that the near side of the galaxy is in the north. The positions of various features on the map are identified by arrows. Streaming motions are clearly present in the H I arms. This is shown in the figure by the local curvature of the velocity contours inside the arms near the minor axis.

The feature labeled A–B–C on the H I map corresponds to the main optical arm in the south, which is on the far side of the galaxy. The velocity contours bend in a backward-C pattern, indicating that the velocities near the H I arm shift toward smaller values. Small velocities on the far side minor axis correspond to radial inward motion. This shift persists all the way to point C on this arm and then disappears, presumably because C is close to the major axis where the line-of-sight velocity is dominated by rotation. The magnitude of the line-of-sight velocity shift on the minor axis is about 10 km s⁻¹.

The nature of the velocity shift in the southern H I arm is interesting. For a small length along the arm, from A to B, there is an abrupt shift toward negative line-of-sight velocity at the inner edge of the H I concentration, indicative of a shock front that slows down the outward-moving interarm gas at smaller radii and makes it stream inward inside the arm. Such shock fronts are rarely observed directly like this. For a longer length along the H I arm, from A to C, there is another abrupt shift in velocity at the outer edge of the arm, indicative of a rarefaction front that returns the gas to its high outward velocity.

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in the next interarm region. These sharp features may be present elsewhere in the spirals, but their observation at this location is most favorable because the telescope beam (the lower left-hand corner of the map) has its smallest dimension perpendicular to the arms here.

The general pattern of streaming motions in the southern H i arm of NGC 925 is a signature of gas flow inside corotation. The detailed features are not the same as those predicted by analytical studies (Roberts 1969). The analytical studies for a one-component, non–self-gravitating fluid in a weak spiral potential have only one abrupt velocity transition, at the inner edge of the shock, and then a gradual acceleration of the gas toward higher radial velocities as it moves through the arm to the interarm. The same smooth expansion pattern occurs for cloudy flows (Hausman & Robert 1984) that differ primarily by not having a sharp shock on the inner edge. Neither of these flows would give a C-shaped velocity pattern on the minor axis. The gas near point A seems to have an equally sharp transition leaving the H i arm as it does entering the arm, and, where the resolution is poor and sharp velocity jumps cannot be seen, the velocity contours are still equally curved on both sides of the arm. This means that the gas does not accelerate much to higher radial speeds while it is inside the H i arm, but maintains about the same speed in the arm and then accelerates rather abruptly as it leaves. The same conclusion could be obtained from the nearly uniform profile of H i column density across the arm, since the column density is inversely proportional to the perpendicular speed. Thus, the gas has a broad and nearly uniform maximum in column density in the H i arm, rather than a single peak at the shock front and a gradual decrease toward larger radii. This uniformity of the arm compression could be the result of self-gravity, as suggested by Lubow, Cowie, & Balbus (1986).

The same pattern of velocity shifts, including beam-smeared shock and rarefaction fronts, is present, although not as prominent, in the northern arm, from D to E, with a positive line-of-sight velocity shift in this case. Because this arm is on the near side of the galaxy, such positive velocity perturbations indicate inward-streaming motions here too. Thus, section D–E is also inside corotation.

The H i column density also shows spiral arms outside these two main optical arms, in the south from the eastern major axis to just beyond the minor axis, and in the north from the western major axis nearly all the way around to the eastern major axis. There is streaming motion there too.

The southern outer arm is indicated by arrows F–G–H, although it begins slightly to the east of F. Beyond G, it is not visible in the figure as an H i density peak, but it still shows up in the streaming motions. Beyond H, we lose information about this arm because the H i is too faint. The velocity contours in the figure indicate that the streaming motions are radially inward at F but radially outward from G to H and beyond. This is the signature of a transition from inside corotation to outside
corotation in conventional models, in which case corotation would be near the southern minor axis between F and G.

The northern outer arm is indicated by I–J–K–L. The streaming motions are positive on the line of sight from I to J and negative from K to L, so corotation could be between J and K in the north.

Considering the galaxy inclination of 55°8, the galactocentric distance of a point on the minor axis is 1/ cos 55.8° = 1.78 times the projected distance. The projected distances of points G and K from the galaxy center at δ = 33°21'4 are 3'0 and 4'0, respectively, which correspond to 14.4 and 19.3 kpc deprojected for the assumed galaxy distance of 9.3 Mpc. The radius at 25 mag arcsec−2 is R25 = 14.2 kpc, and the deprojected optical bar half-length is 5.4 kpc, where the bar ends and the outer spiral system begins. If these points G and K are near corotation, then corotation is at an average Rcr ~ 17 kpc, which is ~3 bar radii and ~1.2R25.

The rotation curve for NGC 925 was given in Pisano et al. (1997). For the deprojected corotation distance of 6°2 = 374° = 16.8 kpc, the rotation speed is ~130 km s−1, which gives the spiral arms a pattern speed of 7.7 km s−1 kpc−1. There is apparently no inner Lindblad resonance (ILR) because of the slowly rising inner rotation curve, and the outer Lindblad resonance (OLR) is too far out in the disk to observe. If the rotation curve remains flat beyond 6°2, then the OLR is at a distance of 1.7 times the corotation distance, which would correspond to 10°5, or 28 kpc. The apparent lack of an ILR requires confirmation from higher resolution gas observations, because sometimes CO in the inner disk reveals a steep rise that was not evident in H I (e.g., Sempere & Garcia-Burillo 1997).

3. DISCUSSION

Stellar orbit theory suggests that corotation of the bar in a barred galaxy cannot be inside the bar (Contopoulos 1981). As a result, it was generally assumed that corotation was actually near the end of the bar. Now it seems this is only approximately true for early-type galaxies since Rcr ~ 1.2Rbar on average (Elmegreen 1996a), placing corotation in the spiral region. It may not even be close for late-type galaxies, if NGC 925 is typical.

The implication of our observations of NGC 925 is either the bar and spiral rotate separately (e.g., Sellwood & Sparke 1988) or the bar + spiral pattern rotates very slowly compared with early-type bars.

REFERENCES

Combes, F., & Elmegreen, B. G. 1993, A&A, 271, 391
Contopoulos, G. 1981, A&A, 81, 198
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R., Paturel, G., & Fouque, P. 1991, Third Reference Catalog of Bright Galaxies (New York: Springer) (RC3)
Elmegreen, B. G. 1996a, in ASP Conf. Ser. 91, Barred Galaxies, IAU Colloq. 157, ed. R. Buta, B. G. Elmegreen, & D. Crocker (San Francisco: ASP), 197
Elmegreen, B. G., & Elmegreen, D. M. 1985, ApJ, 288, 438
Elmegreen, D. M. 1996b, in ASP Conf. Ser. 91, Barred Galaxies, IAU Colloq. 157, ed. R. Buta, B. G. Elmegreen, & D. Crocker (San Francisco: ASP), 23
Garcia-Burillo, S., Sempere, M. J., & Combes, F. 1994, A&A, 287, 419
Gottesman, S. T. 1980, AJ, 85, 824
Haussmann, M. A., & Roberts, W. W., Jr. 1984, ApJ, 282, 106
Lubow, S. H., Cowie, L. L., & Balbus, S. A. 1986, ApJ, 309, 496
Noguchi, M. 1996, ApJ, 469, 605
Pisano, D. J., Wilcots, E. M., & Elmegreen, B. G. 1997, AJ, submitted
Roberts, W. W. 1969, ApJ, 158, 123
Sellwood, J. A., & Sparke, L. S. 1988, MNRAS, 231, 25P
Sempere, M. J., Combes, F., & Casoli, F. 1995a, A&A, 299, 371
Sempere, M. J., & Garcia-Burillo, S. 1997, A&A, 325, 769
Sempere, M. J., Garcia-Burillo, S., Combes, F., & Knapen, J. H. 1995b, A&A, 296, 45
Silberman, N. A., et al. 1996, ApJ, 470, 1
Wevers, B. M. H. R., van der Kruit, P. C., & Allen, R. J. 1986, A&AS, 66, 505