Mon. Not. R. astr. Soc. (1988) **231,** *Short Communication,* 25P–31P

Pattern speeds in barred spiral galaxies

J. A. Sellwood *Department of Astronomy, The University, Manchester M13 9PL*

L. S. Sparke *Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, The Netherlands*

Accepted 1988 January 4. Received 1987 December 23

Summary. Current theoretical ideas of the pattern speeds of the bar and spiral arms in SB galaxies appear to conflict with the observational evidence. This difficulty can be avoided if the spiral arms have a lower pattern speed than the bar. We present evidence of multiple pattern speeds in our N-body simulations, and show that, though the spiral continually breaks from and reconnects to the bar, the morphology of the pattern at all times resembles that of barred galaxies in the sky. We briefly discuss how the gas might respond to the multiple patterns.

1 Introduction

It is customary to assume that the spiral arms in a barred galaxy have the same pattern speed as the bar. It is also generally believed that galactic bars rotate fast enough that corotation lies not far beyond the end of the bar. These two common suppositions together imply that the spiral arms should lie mostly outside their corotation radius.

Unfortunately, this conclusion appears to conflict with other evidence of the pattern speeds of the spiral arms in barred galaxies. Several barred galaxies in the *Hubble Atlas* (Sandage 1961), e.g. M83, NGC 1300, 7741, have dust lanes clearly on the *inner* (concave) edges of the spiral arms, though not always for the whole length of the arm. These dust lanes are usually interpreted as regions of maximum gas compression, which is expected to occur just before the gas reaches the potential minimum as it streams through the pattern (e.g. Roberts 1969). Their occurrence on the inner edge of the arm would therefore indicate that the spiral arms lie inside corotation, for then gas overtakes the pattern. Ondrechen & van der Hulst (1987) report detailed observations of the velocity field of NGC 1365, a strongly barred galaxy; their fig. 5 appears to indicate that the gas flows inward in the arms on the minor axis, suggesting that the spiral there is inside corotation.

Petrou & Papayannopolous (1986) pointed out that this major inconsistency in the theory of barred spiral galaxies can be resolved if the bar ends well before corotation. We find this suggestion unattractive because there are a number of independent lines of argument which favour a high pattern speed for the bar:

(i) Kent (1987) has estimated the pattern speed in the SB0 galaxy NGC 936 from the stellar velocity field and finds that corotation is close to, and possibly even just inside, the end of the bar.

(ii) Studies of stellar orbits in bar-like potentials led Contopoulos (1980) and others to conclude that self-consistent bars should end at or perhaps just inside the corotation resonance.

(iii) The simulations by Sanders & Tubbs (1980) of gas flow in rapidly tumbling barred potentials produced gas flow patterns which corresponded most closely to that observed for the barred spiral NGC 5383 when corotation was just beyond the end of the bar.

(iv) The straight dust lanes frequently seen in galactic bars, usually interpreted as shocks, require a pattern speed sufficiently fast that corotation is just beyond the end of the bar (see e.g. the review by Prendergast 1983).

(v) The global instability exhibited by numerous N-body simulations (Miller & Prendergast 1968; Hohl 1971; Zang & Hohl 1978; Miller & Smith 1979; Sellwood 1980, 1981, 1985; Combes & Sanders 1981, and others) leads to a strong rapidly tumbling bar. The pattern speed of the linear instability is quite high (e.g. Kalnajs 1978) as the theory would suggest (Toomre 1981) and these linear modes develop into strong bars (Athanassoula & Sellwood 1986). It is tempting to identify these N-body systems with bars observed in real galaxies; the N-body bar studied by Sparke & Sellwood (1987), which ended just inside corotation, had a structure and velocity field closely resembling that observed by Kormendy (1983) for NGC 936.

We propose instead that the spirals have a different, much lower, pattern speed than does the bar. The usual assumption that the pattern speeds are the same is prompted by two considerations. First, if the spirals are the driven response of the outer disc to the rotating bar, as calculated by Sanders & Huntley (1976), Roberts, Huntley & van Albada (1979), Schwarz (1981) and others, then they must have the same pattern speed as the bar. Secondly, if the pattern speed of the bar differed from that of the arms, we might expect the spirals to start at a random azimuth with respect to the bar, whereas they mostly seem to start from the ends of the bar. In this paper we show that neither of these considerations is compelling, and present evidence from N-body simulations that multiple pattern speeds are quite common. A similar suggestion was made in the recent paper by Tagger *et al.* (1987).

2 N-body results

2.1 PATTERN SPEEDS

In a number of published simulations (Sellwood 1985; Sellwood & Athanassoula 1986; Sparke & Sellwood 1987), an initially unstable disc develops both a rapidly tumbling bar and a spiral pattern with a significantly lower angular frequency. We reproduce in Fig. 1 the contour plot of the power spectrum of the two-armed ($m=2$) component of the density distribution, taken from Sparke & Sellwood (1987, hereafter Paper I). The two horizontally extended peaks indicate the coexistence of two coherent patterns, both early in the run (a) and at later times (b). The inner, faster peak corresponds to the bar, the outer, slower peaks, to spiral patterns; the slower spiral in (b) lasts for a considerable time. Fig. 5(d) of Sellwood (1985) and Fig. 4(c) of Sellwood & Athanassoula (1986) show similar behaviour in two other, quite different models.

Though multiple pattern speeds frequently appear in N-body simulations, their origin is not clear; this is likely to remain so until the general problem of the origin of spiral structure is solved. In the particular example we illustrate in Fig. 2, the outer pattern may be of the 'edge-mode' type hinted at by Toomre (1981). However, this is clearly not the case in Sellwood's (1985) simulation

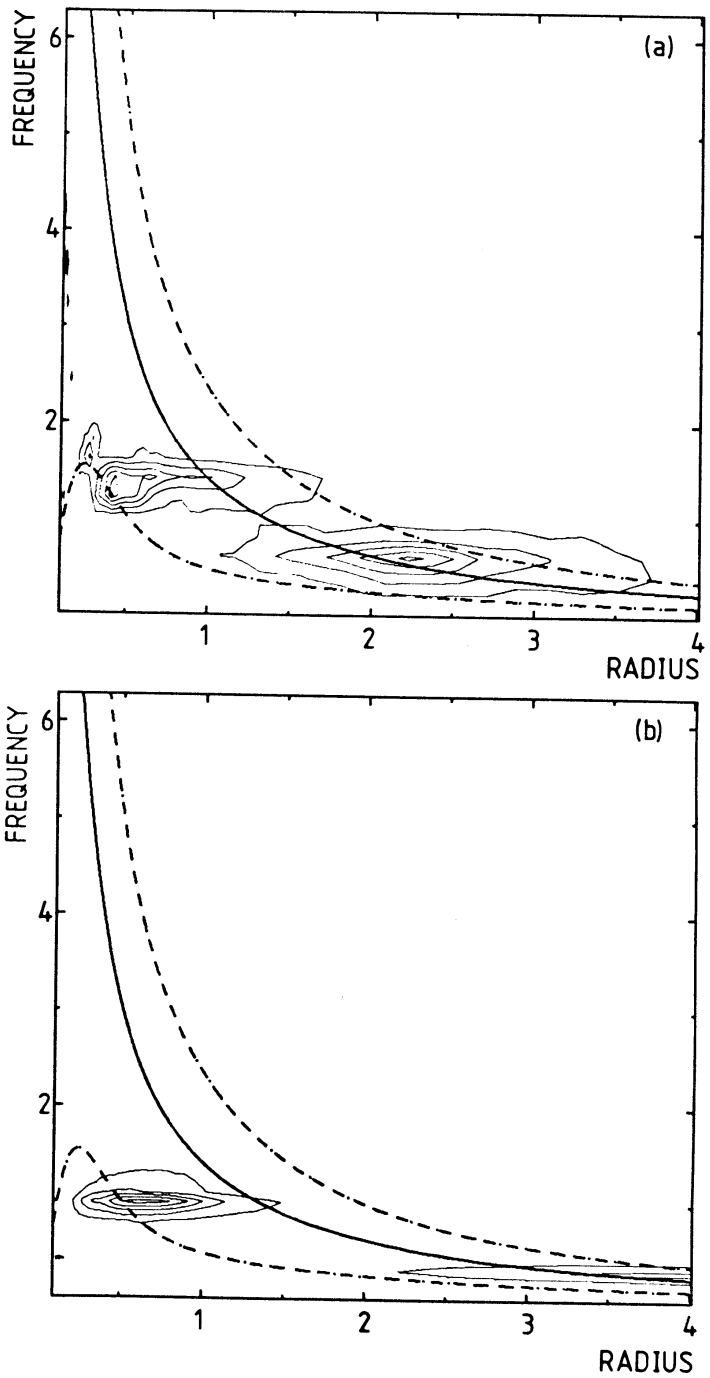
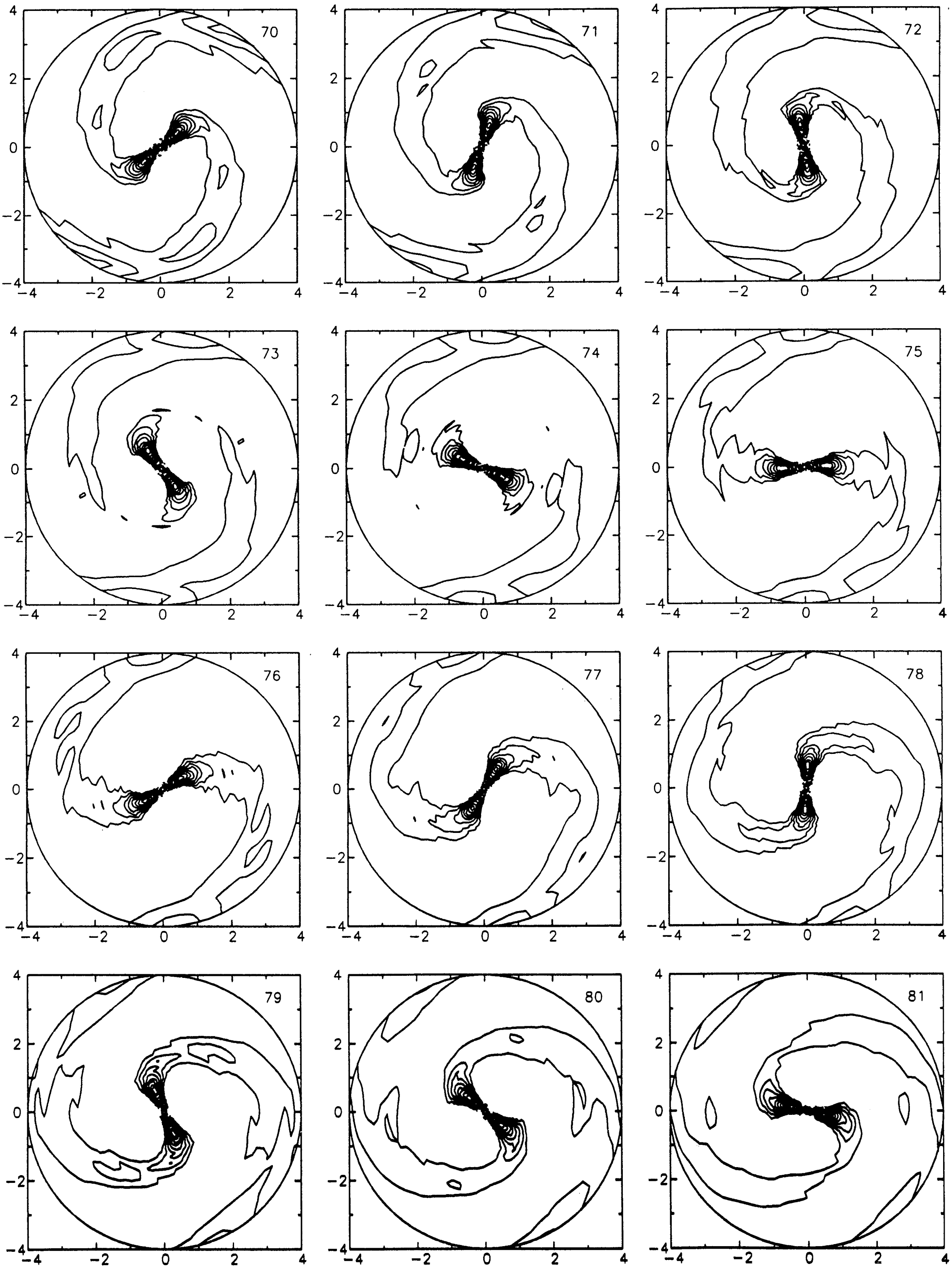


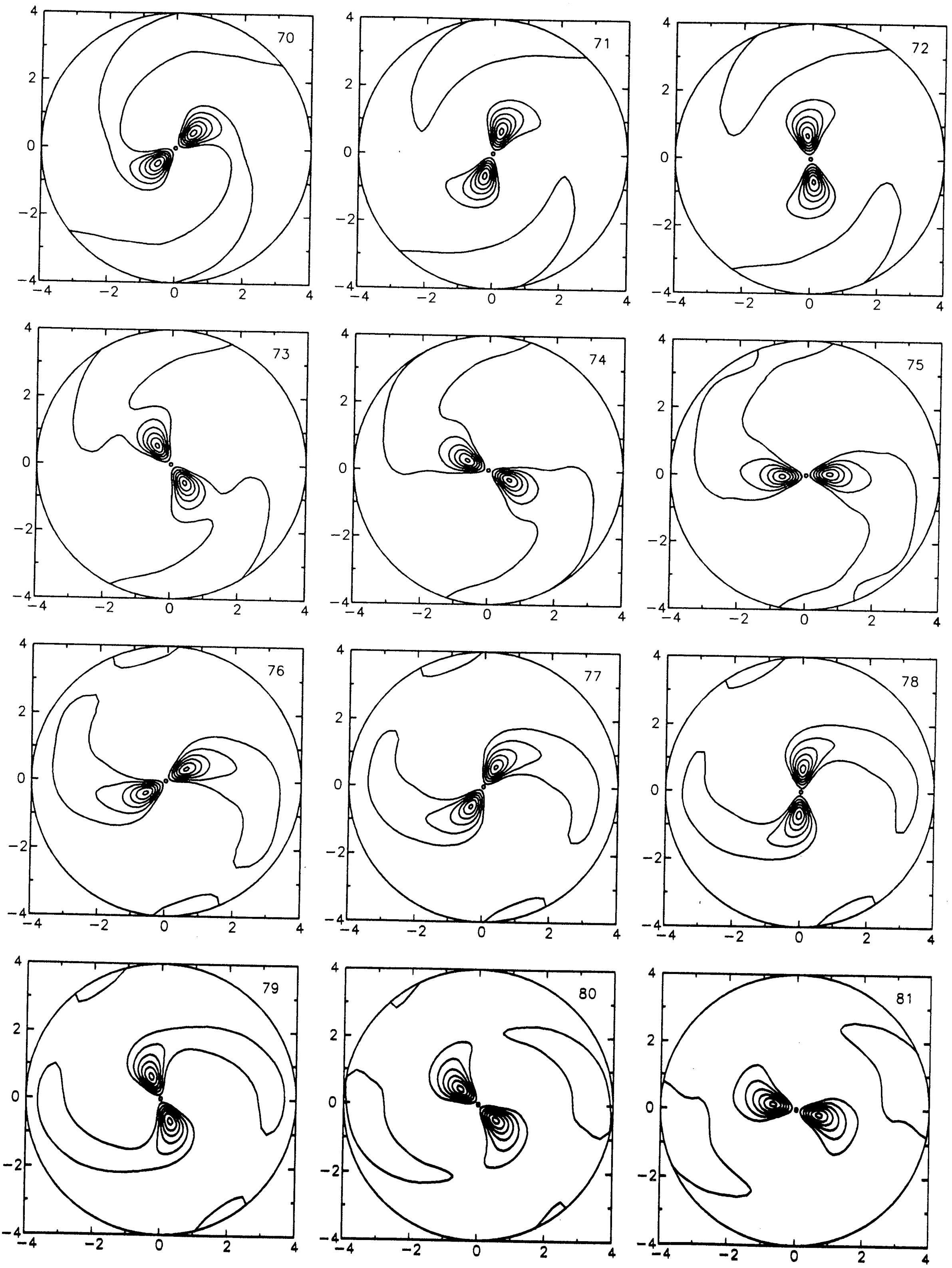
Figure 1. Contours of power as a function of frequency and radius during (a) the early and (b) the later stages of the simulation reported in Paper I. The locations of the ridges indicate the pattern speeds and radial extents of large amplitude bisymmetric features in the model. The smooth curves show the radial variations of 2Ω (full drawn) and $2\Omega \pm \kappa$ (dashed) for the initial axisymmetric model, so that in the later stages (b) they are relevant only far out in the disc.

of the Bahcall, Schmidt & Soniera (1982) model of our Galaxy: there the spiral pattern is nowhere near the edge. There are several possible alternative explanations. The spirals could be: a hitherto unidentified class of spiral instability, or they could be swing-amplified noise (Toomre, in preparation), or they are driven responses to the large amplitude bars, through three mode coupling (Tagger *et al.* 1987; Synget *et al.* 1988). It is beyond the scope of this paper to discuss these ideas in detail.



(a)

Figure 2. Contours of the fractional perturbation in (a) the density and (b) the potential in the same simulation as Fig. 1, at a sequence of times chosen to illustrate one beat period between the two patterns. Only the low-order even Fourier harmonics contribute and the amplitude of the perturbation is everywhere normalized by the local axisymmetric value in the disc (the bulge is not included). The contour levels in (a) are at 10, 30, 50, . . . , 130 per cent of the local axisymmetric density; in (b) the contour levels are one-tenth of those in (a).



(b)

Figure 2 – *continued*

2.2 BAR–SPIRAL CONTINUITY

Although the two patterns in Fig. 1(b) rotate at different rates, the spiral appears generally to connect to the bar (see fig. 1 of Paper I). In Fig. 2(a) we show contours of the (symmetrized) disturbance density at a number of moments to illustrate one complete beat cycle between the bar and the spiral. Though this time sequence makes it clear that the bar is indeed rotating faster than the spiral, at most times one gains the impression that the spiral starts from the ends of the, sometimes lengthened, bar. Whether or not the spiral appears connected to the bar in this figure depends, in some frames, on the choice of contour levels, but the ridge-line of the spiral pattern extends ahead of the bar only at times 74 and 75.

In fact, not every barred spiral galaxy has arms that appear to begin at the ends of the bar. A few clear exceptions are NGC 1073, 4548 and 5383 (all in the *Hubble Atlas*, Sandage 1961); the spiral arms in these galaxies start slightly ahead of the bar. We would identify our model at times such as 74 and 75 with such cases.

2.3 POTENTIAL FORCING

The gas in a barred spiral galaxy will respond to the total perturbation force from both the bar and the stellar spiral. Might we therefore expect to see two spiral patterns in the gas: the forced response to the bar (e.g. Sanders & Huntley 1976) in addition to that driven by the outer spiral at a different pattern speed?

We have not undertaken any calculation of the behaviour of a gas component in such a time-dependent potential: hydrodynamic simulations in this situation will be considerably more difficult than for the simpler case of a single pattern speed. However, we do not expect the forced response to the bar potential to extend far outside the region where that potential itself is strong. Although Sanders & Huntley (1976) found an extensive spiral response to a mild oval distortion, their adopted non-axisymmetric potential decreased very slowly with radius; Sanders & Tubbs (1980) showed that the response in the outer disc is much weaker when the bar has a realistic potential. Because the field of a finite length bar decays as a quadrupole, the bar must be extremely strong if it alone is to produce a spiral response at large radii (e.g. Roberts *et al.* 1979).

Fig. 2(b) shows the total disturbance potential (also symmetrized) of the model at the same instants as in Fig. 2(a). This clearly shows that the comparatively weak spiral is still strong enough to dominate the disturbance force except within the bar itself. It seems reasonable to suppose that the gas response will mainly be determined by the steadily rotating pattern that locally dominates the potential, i.e. the gas response will resemble that in published barred potential models in the barred region and spiral potential models in the spiral region. We would not, therefore, expect to see two superposed spiral patterns in the disc.

Our argument suggests that barred galaxies with well developed outer spiral structure *must* have spiral density waves in the stellar component of the outer disc, in order to produce strong responses in the gas. As the stellar *response* to forcing by a steady bar cannot be spiral in form (e.g. Sanders & Huntley 1976), the spiral must be excited by some other mechanism; and this at once opens up the possibility that the pattern speed could be different from that of the bar.

3 Discussion

We have argued that the spiral arms of barred galaxies need not rotate at the same angular frequency as the bar. We have presented one N-body experiment in detail, and referred to two others in the literature, in which a bar coexists with a spiral of a much lower pattern speed. Few other reports of N-body experiments present the kind of diagnostic that would enable multiple pattern speeds to be identified, but in our simulations such behaviour is quite common. In fact, it occurs in every model where the disc extends well beyond the 'turn over' radius of the rotation curve. It is therefore reasonable to expect that if this phenomenon occurs in galaxies at all, it may happen in the majority of cases.

If this were so, it would resolve the apparent conflict between the locations of the corotation resonances for the bar and the spiral. Because the angular rotation rates are different for each pattern, it is possible to reconcile the belief that the bar extends almost to *its* corotation radius with the indications that at least part of the spiral also lies within its own (larger) corotation radius.

It is natural to extend this idea immediately to multiple spiral patterns, which also occur frequently in our simulations. The coexistence of several spiral patterns in nature is evident from the multiple distinct spiral patterns in galaxies such as NGC 210, 3810 and 5364 (all pictured in Sandage 1961). In these cases, the radial extents of coexisting patterns do not appear to overlap to any great extent, but in others they might. Roelfsema & Allen (1985) pointed out that it would be difficult to account for the extensive spiral pattern in UGC 2885 with just a single pattern speed, but the difficulty could again be avoided if the spiral wave in that galaxy were to be composed of two (or more) patterns, with differing angular rotation rates.

Acknowledgments

We would like to thank Richard James for comments on the manuscript. JAS acknowledges the support of an SERC Advanced Fellowship.

References

Athanassoula, E. & Sellwood, J. A., 1986. *Mon. Not. R. astr. Soc.*, **221**, 213.

Bahcall, J. N., Schmidt, M. & Soniera, R. M., 1982. *Astrophys. J.*, **258**, L23.

Combes, F. & Sanders, R. H., 1981. *Astr. Astrophys.*, **96**, 164.

Contopoulos, G., 1980. *Astr. Astrophys.*, **81**, 198.

Hohl, F., 1971. *Astrophys. J.*, **168**, 343.

Kalnajs, A. J., 1978. In: *Structure and Properties of Nearby Galaxies, IAU Symp. No. 77*, p. 113, eds Berkhuisjen, E. M. & Wielebinski, R., Reidel, Dordrecht, Holland.

Kent, S. M., 1987. *Astr. J.*, **93**, 1062.

Kormendy, J., 1983. *Astrophys. J.*, **275**, 529.

Miller, R. H. & Prendergast, K. H., 1968. *Astrophys. J.*, **151**, 699.

Miller, R. H. & Smith, B. F., 1979. *Astrophys. J.*, **227**, 407.

Ondrechen, M. P. & van der Hulst, J. M., 1987. *Astrophys. J.*, submitted.

Petrou, M. & Papayannopoulos, T., 1986. *Mon. Not. R. astr. Soc.*, **219**, 157.

Prendergast, K. H., 1983. In: *Internal Kinematics and Dynamics of Galaxies, IAU Symp. No. 100*, p. 215, ed. Athanassoula, E., Reidel, Dordrecht, Holland.

Roberts, W. W., 1969. *Astrophys. J.*, **158**, 123.

Roberts, W. W., Huntley, J. M. & van Albada, G. D., 1979. *Astrophys. J.*, **233**, 67.

Roelfsema, P. R. & Allen, R. J., 1985. *Astr. Astrophys.*, **146**, 213.

Sandage, A., 1961. *The Hubble Atlas of Galaxies*, Carnegie Institute of Washington.

Sanders, R. H. & Huntley, J. M., 1976. *Astrophys. J.*, **209**, 53.

Sanders, R. H. & Tubbs, A. D., 1980. *Astrophys. J.*, **235**, 803.

Schwarz, M. P., 1981. *Astrophys. J.*, **247**, 77.

Sellwood, J. A., 1980. *Astr. Astrophys.*, **89**, 296.

Sellwood, J. A., 1981. *Astr. Astrophys.*, **99**, 362.

Sellwood, J. A., 1985. *Mon. Not. R. astr. Soc.*, **217**, 127.

Sellwood, J. A. & Athanassoula, E., 1986. *Mon. Not. R. astr. Soc.*, **221**, 195.

Sparke, L. S. & Sellwood, J. A., 1987. *Mon. Not. R. astr. Soc.*, **225**, 653 (Paper I).

Synget, J. F., Tagger, M., Athanassoula, E. & Pellat, R., 1988. *Mon. Not. R. astr. Soc.*, in press.

Tagger, M., Synget, J. F., Athanassoula, E. & Pellat, R., 1987. *Astrophys. J.*, **318**, L43.

Toomre, A., 1981. In: *Structure and Evolution of Normal Galaxies*, eds Fall, S. M. & Lynden-Bell, D., Cambridge University Press.

Zang, T. A. & Hohl, F., 1978. *Astrophys. J.*, **226**, 521.