Most Real Bars are Not Made by the Bar Instability

J. A. Sellwood

Department of Physics & Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway NJ 08854-8016, USA
e-mail: sellwood@astro.rutgers.edu

Abstract. Having once thought that we understood how some galaxies were barred and had difficulty accounting for the absence of bars in others, it now seems that we have the opposite problem. Most real galaxies have centres dense enough to inhibit bar formation, even if they have massive discs. This is also true for barred galaxies, which therefore could not have acquired their bars as a result of a self-excited, global instability. There is a hint from the morphology of galaxies in the Hubble Deep Fields that the growth of bars might be a slow or secular process. Here I discuss possible mechanisms that could form bars long after the disc is assembled.

1. Introduction

I am probably not the only person who once thought that the bar instability was responsible for the bars we see in a decent fraction of nearby galaxies (Sellwood & Wilkinson 1993). While understanding the absence of strong bars in most galaxies was a major headache for galaxy dynamicists (Ostriker & Peebles 1973; Toomre 1974), we took comfort from the fact that we thought we knew why some galaxies have bars. Now we understand why galaxies are not barred, we can no longer claim to comprehend the origin of bars – our problem has inverted!

I have two reasons for doubting that bars, especially those in bright galaxies, could have formed through the usual global instability. The first, which has been evident for some time, is that many barred galaxies have strong inner Lindblad resonances (ILRs) and the second is the recent claim by Abraham et al. (1999; see also Merrifield, this volume) that bars were less common at $z > 0.5$. The latter result is clearly still quite tentative but, even if it went away, the ILRs in bars are themselves ample evidence against straightforward instabilities.

2. Inner Lindblad resonances in bars

A number of lines of evidence all suggest that many bars possess ILRs. Recall that the gravitational stresses from a bar drive gas inwards towards the center until an ILR is encountered, where it piles up in a ring (e.g. Athanassoula 1992). Optical nuclear rings with diameters of a few hundred pc (Buta & Crocker 1993), often the sites of vigorous star formation, are seen in many, though not quite all, barred galaxies; a particularly beautiful case is the HST image of NGC 4314 (Benedict et al. 1998). Ring-like concentrations of molecular gas, often with
“twin peaks” morphology, are now being observed with molecular interferometer arrays \(\textit{e.g.}\) Helfer & Blitz 1995; Turner 1996; Kenney 1997; Sakamoto \textit{et al.} 1999). Further, Athanassoula (1992) argued that gas flow models could produce shocks at the positions of the offset dust lanes along the bar in many galaxies only if a strong ILR were present. Those barred galaxies for which the observed gas velocity field has been modelled all appear to have ILRs (Duval & Athanassoula 1983; Lindblad \textit{et al.} 1996; Regan \textit{et al.} 1997; Weiner \textit{et al.} 1999). Finally, there is strong evidence for an ILR in the bar of the Milky Way (Binney \textit{et al.} 1991; Weiner & Sellwood 1999).

2.1. Disc Stability

Much of this overwhelming body of evidence in favour of a central density high enough to ensure an ILR has been known for some time. Yet it did not seem to represent much more than a nagging worry because we did not fully understand how galaxy disks were stabilized. Now that we know a high central density really does stabilize a galaxy, this minor worry has suddenly become serious.

Toomre (1981) argued that a dense centre could prevent the bar instability by inserting an ILR to cut the feedback to the swing-amplifier. Only numerical simulations with reasonable particle numbers and good time and spatial resolution are able to reproduce the correct behaviour in the central regions and confirm this prediction. They have now established that galaxy models containing massive discs can be dynamically cool and yet not form bars (Sellwood 1985; Sellwood & Moore 1999; Sellwood 1999). Rubin \textit{et al.} (1997) and Sofue \textit{et al.} (1999) show that virtually all bright galaxies \(V_{\text{max}} \geq 150\ \text{km s}^{-1}\) have dense centres – the reason for the stability of real galaxies is now clear.

If the mass distribution in barred galaxies today is such that it should have inhibited a bar from forming, why are these galaxies barred? We can dismiss two obvious ideas. If bars formed with much higher pattern speeds and have since slowed down (without getting longer, see below) then co-rotation would lie well beyond the end of the bar, which contradicts much of the evidence already cited as well as direct measurements (Merrifiend & Kuijken 1993; Gerssen \textit{et al.} 1999). Perhaps the mass distribution was originally more uniform, but enough gas has subsequently been driven into the centre to create the ILR. This idea seems physically reasonable since as little as 1–2% of the galaxy mass, together with the supporting response of the stars, is sufficient (Sellwood & Moore 1999). However, this same process weakens or destroys the bar, as has been argued by Norman and his co-workers (Hasan & Norman 1990; Pfenniger & Norman 1990) and reproduced in simulations (Friedli 1994; Norman \textit{et al.} 1996).

3. Hubble Deep Fields

The study of the barred galaxy fraction as a function of redshift by Abraham \textit{et al.} (1999; see also Merrifield, this volume) raises a further difficulty for the bar instability picture. They find very few strongly barred galaxies at \(z > 0.5\), suggesting that bars develop long after the discs of these galaxies are assembled. This result may suggest a gradual build-up of the disc until the rapid dynamical instability occurs. However, late infalling material probably contributes to the outer disc, and not to the central density \(\textit{e.g.}\) Simard \textit{et al.} 1999), and so will
have less effect on global stability and, furthermore, such an idea would not avoid the stabilizing effect of the observed dense centres.

4. Other Bar-Formation Mechanisms

The above discussion suggests that we should abandon the idea that bars are caused by the global dynamical instability. If this most obvious mechanism for bar formation is excluded, what are the alternatives?

One possibility is an encounter with another galaxy which triggers a bar (e.g. Noguchi 1987; Gerin et al. 1990; Mihos et al. 1997). There is some evidence for higher barred fraction in dense environments (Elmegreen et al. 1990; Giuricin et al. 1993), suggesting that this does occur in practice. However, the idea is unattractive for two reasons: first, interactions were more common in the early universe, so the bar fraction should build up quickly, in contradiction to Abraham et al. Second, Miwa & Noguchi (1998) find that bars formed through tidal encounters generally have rather low pattern speeds, whereas most bars are believed to rotate rapidly, as noted above.

Lynden-Bell (1979) argued for a gradual secular bar growth through orbit trapping. However, his mechanism would again form bars having slow figure rotation, whereas almost all evidence points to rapid figure rotation.

I currently favour episodic growth, which I reported in some of my early simulations (Sellwood 1981). In this process, a short, weak bar can become longer and stronger through trapping of erstwhile disc particles into the bar; strong spiral patterns, which carry away angular momentum, can add many particles to the bar. It differs from Lynden-Bell’s mechanism because changes occur in ~ 1 orbital period and depend crucially on the phase of the spiral relative to the bar. After one such spiral pattern, the bar is significantly longer and slightly slower than before, but co-rotation remains just beyond the end of the bar. It should be noted, however, that all simulations so far in which I have witnessed this process have required an initial seed bar.

5. Conclusions

If bars were formed by the global bar instability, then (1) they probably should form a bar early in a galaxy’s life and (2) they should not form when the centre is dense. Both predictions are inconsistent with observations, the second much more decisively, arguing strongly that bars were not formed in this manner.

Thus an alternative bar-forming mechanism is needed. I propose one such possibility, but the idea is not fully worked out. Ideally some observational test is needed that would be able to distinguish a bar formed through this, or any other secular process, from one formed through a global dynamical instability. It would also be desirable to be able to predict the distribution of bar strengths in galaxies today, although this may have to await substantial progress in our understanding of the late stages of galaxy formation.

Acknowledgments. This work was supported by NSF grant AST 96/17088 and NASA LTSA grant NAG 5-6037.
References

Abraham, R. G., Merrifield, M. R., Ellis, R. S., Tanvir, N. & Brinchman, J. 1999, MNRAS, 308, 596
Athanassoula, E. 1992, MNRAS, 259, 345
Benedict, G. F., Howell, A., Jorgensen, I., Chapell, D., Kenney, J. & Smith, B. J. 1998, STSCI Press Release C98
Buta, R. & Crocker, D. A. 1993, AJ, 105, 1344
Binney, J., Gerhard, O., Stark, A., Bally, J. & Uchida, K. 1991, MNRAS, 252, 210
Duval, M. F. & Athanassoula, E. 1983, A&A, 121, 297
Elmegreen, D. M., Elmegreen, B. G. & Bellin, A. D. 1990. ApJ, 364, 415
Friedli, D. 1994, in Mass-Transfer Induced Activity in Galaxies, ed. I. Shlosman (Cambridge: Cambridge University Press) p 268
Gerin, M., Combes, F. & Athanassoula, E. 1009, A&A, 146, 268
Gerssen, J., Kuijken, K. & Merrifield, M. R. 1999, MNRAS, 306, 926
Giuricin, G., Mardirossian, F., Mezzetti, M. & Monaco, P. 1993, ApJ, 411, 13
Hasan, H. & Norman, C. 1990, ApJ, 361, 69
Helfer, T. T. & Blitz, L. 1995, ApJ, 450, 90
Kenney, J. 1997, in The Central Regions of the Galaxy and Galaxies, IAU Symp. 184, (to appear)
Lindblad, P. A. B., Lindblad, P. O. & Athanassoula, E. 1996, A&A, 313, 65
Lynden-Bell, D. 1979. MNRAS, 187, 101
Merrifield, M. R. & Kuijken, K. 1995, MNRAS, 274, 933
Mihos, J. C., McGaugh, S. S. & de Blok, W. J. G. 1997, ApJ, 477, 79
Miwa, T. & Noguchi, M. 1998, ApJ, 499, 149
Norman, C. A., Sellwood, J. A. & Hasan, H. 1996, ApJ, 462, 114
Noguchi, M. 1987, MNRAS, 228, 635
Ostriker, J. P. & Peebles, P. J. E. 1973, ApJ, 186, 467
Pfenniger, D. & Norman, C. 1990. ApJ, 363, 391
Regan, M. W., Vogel, S. N. & Teuben, P. J. 1997, ApJ, 482, 143
Rubin, V. C., Kenney, J. D. P. & Young, J. S. 1997, AJ, 113, 1250
Sakamoto, K., Okamura, S. K., Ishizuki, S. & Scoville, N. Z. 1999, astro-ph/990645
Sellwood, J. A. 1981, A&A, 99, 362
Sellwood, J. A. 1985, MNRAS, 217, 127
Sellwood, J. A. 1999, in Galaxy Dynamics – A Rutgers Symposium, eds. D. Merritt, J. A. Sellwood & M. Valluri (San Francisco: ASP) 182, p 351
Sellwood, J. A. & Moore, E. M. 1999, ApJ, 510, 125
Sellwood, J. A. & Wilkinson, A. 1993, Rep. Prog. Phys., 56, 173
Simard, L., et al. 1999, astro-ph/9902147
Sofue, Y. et al. 1999, ApJ, in press (astro-ph/9905056)
Toomre, A. 1974, in Highlights of Astronomy, 3, ed. G. Contopoulos (Dordrecht: Reidel) p 457
Toomre, A. 1981, in Structure and Evolution of Normal Galaxies, eds. S. M. Fall & D. Lynden-Bell (Cambridge: Cambridge University Press) p 111
Turner, J. L. 1996, in Barred Galaxies, IAU Colloq. 157, eds. R. Buta, B. G. Elmegreen, D. A. Crocker (San Francisco: ASP), 91 p 143
Weiner, B. & Sellwood, J. A. 1999, ApJ, 524
Weiner, B., Sellwood, J. A., Williams, T. B. & van Gorkom, J. 1999, ApJ, (submitted)