GAS AND STAR DYNAMICS OF GALAXIES

G. CONTOPOULOS
Astronomy Department, University of Athens
Athens, GREECE
and
Astronomy Department, University of Florida
Gainesville, Fl. USA

ABSTRACT. A review of recent developments in three problems is made. (1) Galaxy formation. Quite different patterns are found if the galaxy is mainly gaseous or mainly stellar. In the first case the motions are highly organized, while in the second case they are mostly irregular. (2) Barred galaxies. One can construct roughly self-consistent stellar models for the bar and for the outer spiral, beyond the -4/1 resonance. The stellar orbits near corotation are stochastic, but gas can join smoothly the bar with the outer stellar spiral. (3) Normal Spirals. We found that strong and open spirals (Sb,Sc) terminate near the 4/1 resonance, while weak tight spirals (Sa) can extend all the way to corotation.

1. Galaxy Formation

Galaxies are formed out of initial irregularities in an environment that produces a cluster of galaxies. During the expansion phase angular momentum is transferred to the galaxy not only by its near neighbours, but also by the more numerous distant galaxies (Voglis and Hiotelis 1989, and references therein). After the maximum expansion the galaxy collapses, first along its minor axis and later also along its major axis. Until the collapse of the minor axis (Fig. 1) gas dynamical effects are insignificant. After that phase, however, the differences between a gaseous and a stellar galaxy are enormous (Contopoulos,et al. 1990, 1991). The gas organizes its motions to become mainly circular, while the stars move in a highly irregular way (Fig.2). Thus the gaseous galaxy develops a rotating disc, while the stellar galaxy approaches the form of an elliptical galaxy.

Our first gas calculations were made using Smooth Particle Hydrodynamics (Monaghan and Lattanzio 1985, Durisen et al. 1986) with fixed smoothing length h. While this method shows clearly the development of ordered (circular) motions, it does not represent well regions of high or low

F. Combes and F. Casoli (eds.), Dynamics of Galaxies and Their Molecular Cloud Distributions, 335–342.
© 1991 *IAU. Printed in the Netherlands.*

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press

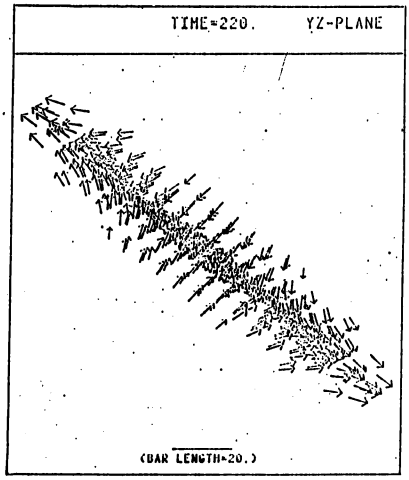

Fig. 1. The velocities in a model galaxy during the collapse of its minor axis. The galaxy still expands along its major axis. This configuration provides the initial conditions for the later evolution of a gaseous and a stellar galaxy.

density. In the first case details smaller than h are lost, while in the second case the particles are far away and behave like stars rather than gas. More recent methods use a variable h and give much better results (Fig.3, Voglis and Hiotelis 1990).

The tidal effects of the other galaxies are in general small after the collapse of the galaxy. However if the time scale of the collapse of the cluster is not much longer than the corresponding time-scale for the galaxy collapse the tidal effects last longer and in some cases they can reverse the rotation of the outer parts of the galaxy. In this way we can explain some galaxies that have opposite rotations in their central and outer parts.

2. Barred galaxies

The bars in barred galaxies can be self-consistent up to corotation (Contopoulos 1980). In fact the orbits inside corotation are elongated along the bar (Figs.4,5). Beyond corotation the orbits in general do not support the bar. However they can support a spiral between the -4/1 resonance and the -2/1 resonance (outer Lindblad resonance) (Contopoulos et al.1989, Contopoulos and Grosbol 1990).

The orbits close to corotation are mainly stochastic. This stochasticity is weak, i.e. the orbits do not approach the center nor do they escape over long times. They form rings around the center with fuzzy boundaries (Fig.6) but

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press

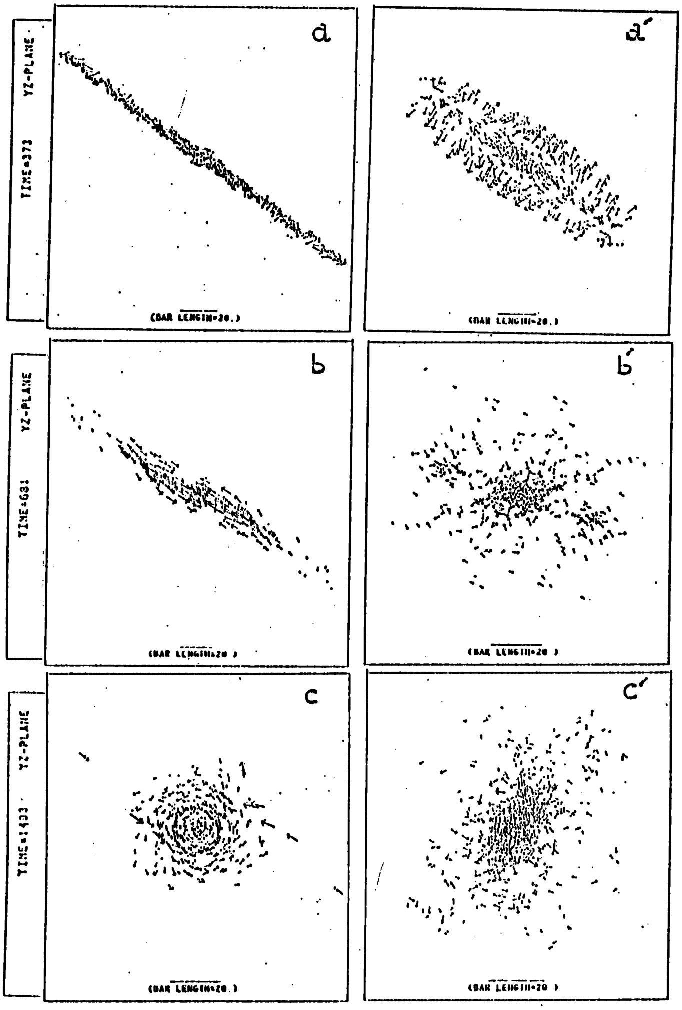

Fig.2. Evolution of a gaseous galaxy [(a),(b),(c)] versus a stellar galaxy [(a'),(b'),(c')] at various times. The ring of Fig. 2c is spurious (it is due to the rather large smoothing length used).

but they do not support the spiral arms. Only in weak spirals such orbits partially enhance the spiral arms for rather long times. We conclude that strong spirals cannot be self-consistent in the region outside and close to corotation.

On the other hand the gas can bridge the region between the end of the bar and the outer stellar spiral, beyond the -4/1 resonance. In fact the gas tends to concentrate along the bar and close to the minimum of the spiral potential,

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press

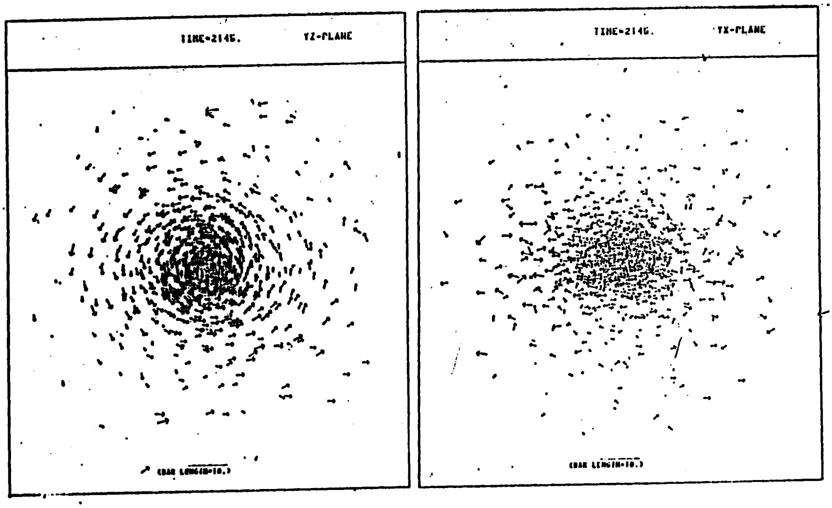

Fig. 3. A slowly rotating gaseous galaxy, with variable smoothing length h. Projection (a) on the plane of rotation and (b) perpendicularly to it.

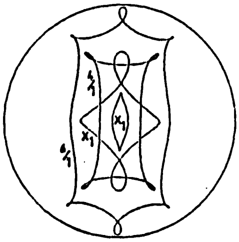

Fig. 4. The main families of periodic orbits in a barred galaxy inside corotation.

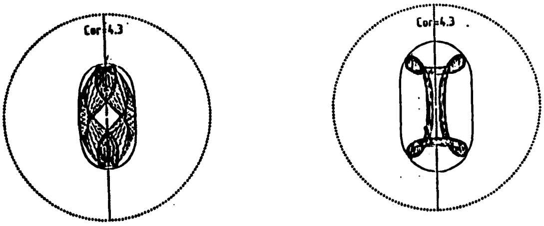

Fig. 5. The main types of non-periodic orbits in a barred galaxy inside corotation.

which is due to stars. But it tends also to join smoothly the maxima of density inside and outside corotation, and extends even a little beyond the outer Lindblad resonance. However if we have only gas beyond corotation the spiral arms are short and stubby. Therefore the existence of a

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press

stellar self-consistent spiral is necessary in order to have an important gas dynamical response. The best results appear when there is also a weak stellar spiral between corotation and the -4/1 resonance.

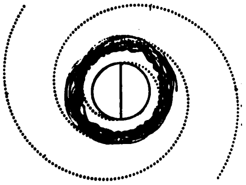

Fig. 6. A stochastic orbit close to corotation

3. Normal Spirals

In order to find self-consistent models of spiral galaxies we must check the agreement between the response and the imposed density both as regards the amplitude and the phase of the spiral. Thus we calculate the quantities

$$R^{*} = \frac{\sigma^{response}}{\sigma^{imposed}} ,$$

and

$$\Delta\theta = \theta^{response} - \theta^{imposed} ,$$

where σ represents the amplitude and θ the arimuth of the maximum of the surface density. R^{*} must be close to 1, while $\Delta\theta$ must be close to zero.

The main spiral component has a -2θ dependence. However if the spiral is strong the -4θ component is also important.

The response density is produced mainly by orbits trapped around the periodic orbits of the imposed spiral field. In the case of strong spirals the most important families of periodic orbits support the spiral up to the 4/1 resonance, but are completely out of phase beyond this

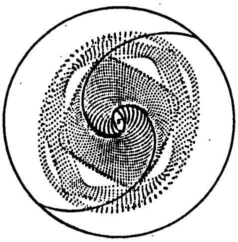

Fig. 7. The main families of periodic orbits in a strong spiral.

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press

resonance (Fig. 7). This phenomenon was observed in a model of NGC 5247 (Contopoulos and Grosbol 1986, 1988), but it is quite general. In a more recent study Patsis, Contopoulos and Grosbol studied 13 galaxies for which sufficient photometric data and velocity curves are available to construct models of the imposed density. In view of the uncertainties as regards the dark matter and the z-thickness we constructed 3 models in each case, assuming that thre observed spiral ends at corotation, or the 4/1 resonance: (L-Co) Linear model ending at corotation
(N-Co) Nonlinear model ending at corotation
and (N-4/1) Nonlinear model ending at the 4/1 resonance.

In Figs. 8a,b,c we give the 3 response models in the case of the galaxy NGC 2997. The corresponding functions R* are given in Figs. 9a,b,c. It is obvious that the results are much better in the nonlinear model ending at the 4/1 resonance. (The scatter of the points beyond the 4/1 resonance is of no importance because we assume only a weak extension of the spiral beyond the 4/1 resonance, and the ratio of two small numbers is very uncertain). The quantity $\Delta\theta$ is also much closer to zero in the N-4/1 case than in the other two cases.

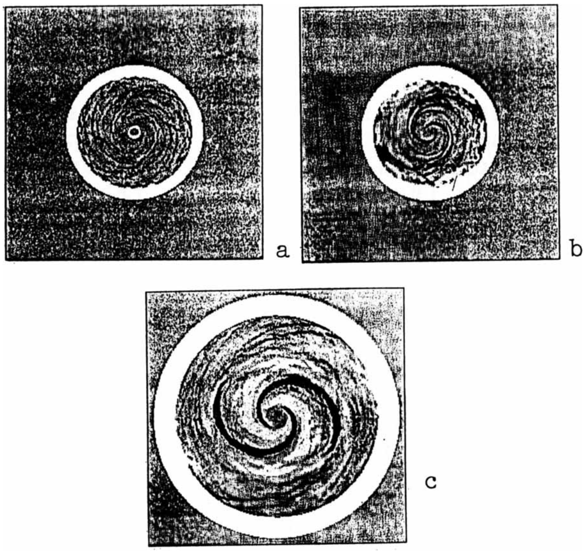

Fig. 8. The best models of the response density in the case of the galaxy NGC 2997 (a) L-Co, (b) N-Co, and (c) N-4/1

Similar results were found in all Sb and Sc galaxies

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press

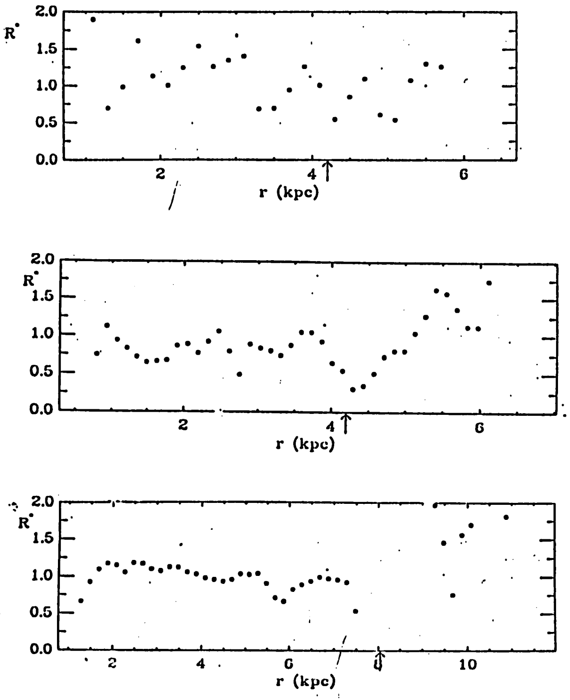

Fig. 9. The ratio R* as a function of r in the 3 models of Fig.8. The arrows mark the 4/1 resonance.

(10 out of 13 cases). In all these cases the best models are the nonlinear ones ending at the 4/1 resonance.

On the other hand in the Sa galaxies (3 cases out of 13) the best models are the linear ones ending at corotation. In these cases the spirals are weak and the linear theory of density waves is applicable. The effects at the 4/1 resonance are not important.

In one case of a model galaxy terminating at the 4/1 resonance we imposed also a spiral field beyond the -4/1 resonance outside corotation and calculated the response of the gas. We found that the gas follows the imposed spiral inside the 4/1 resonance and outside the -4/1 resonance, but does not join the two regions. It seems that in this case the gap between the two resonances is very large to be bridged by the gas as in the case of barred galaxies. It remains to be seen if in other models the gap between the 4/1 and -4/1 resonances is smaller so that the gas can join smoothly the two regions.

5. References

Contopoulos, G. (1980) "How far do bars extend?", Astron. Astrophys. 81, 198-209.

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press

Contopoulos, G., Gottesman, S.T., Hunter, J.H.Jr. and England, M.N. (1989),"Comparison of stellar and gas dynamics of a barred galaxy", Astrophys. J. 343, 608-616.

Contopoulos, G. and Grosbol, P. (1986) "Stellar dynamics of spiral galaxies: nonlinear effects at the 4/1 resonance", Astron. Astrophys. 155, 11-23.

Contopoulos, G. and Grosbol, P. (1988) "Stellar dynamics of spiral galaxies: self consistent models", Astron. Astrophys. 197, 83-90.

Contopoulos, G. and Grosbol, P. (1990), "Orbits in barred galaxies", Astron. Astrophys. Rev. 1, 261-289.

Contopoulos, G. Voglis, N. and Hiotelis, N. (1990), "Galaxy formation: gas dynamics vs stellar dynamics", in Buchler, R. and Gottesman, S. (eds). Astrophysical Nonlinear Fluid Dynamics, N. York Acad.Sci.Ann.(in press).

Contopoulos, G., Voglis, N. and Hiotelis, N. (1991),"Hydrodynamics in a collapsing gaseous protogalaxy", Astron. Astrophys. (in press).

Voglis, N. and Hiotelis, N. (1989), "Simulations of galaxy formation in tidal fields", Astron.Astrophys. 218,1-14.

Voglis, N. and Hiotelis, N. (1990), Astron. Astrophys. (submitted).

https://doi.org/10.1017/S0074180900244446 Published online by Cambridge University Press