DYNAMICS OF SPIRAL GALAXIES

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OUTLINE

PART I – Some interesting topics in the dynamics of spiral galaxies ; morphology of spiral galaxies

PART II – Theory of spiral structure in galaxies

PART II – THEORY OF SPIRAL STRUCTURE

KINEMATICS, DIFFERENTIAL ROTATION, EPICYCLES

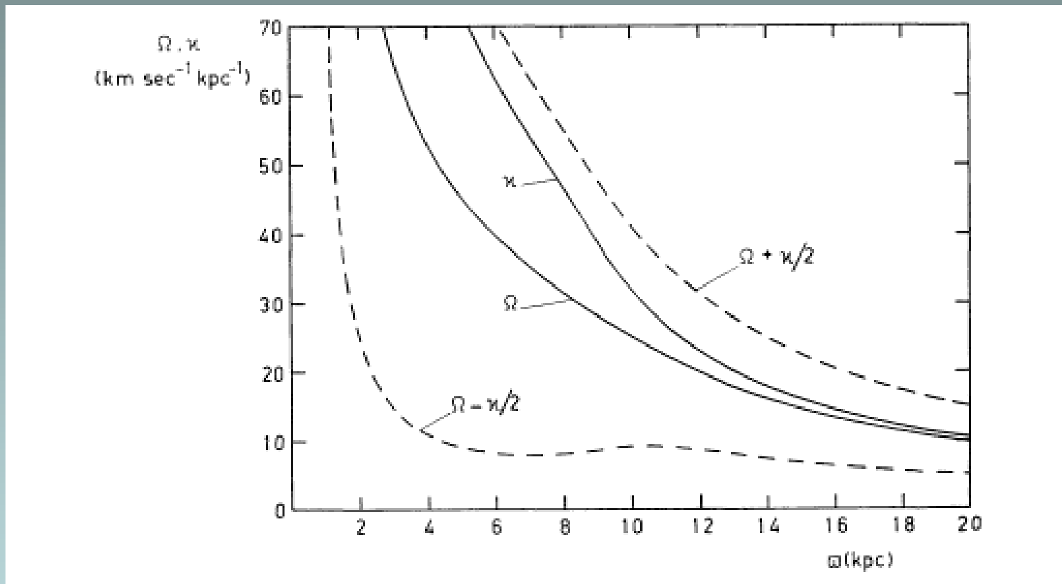
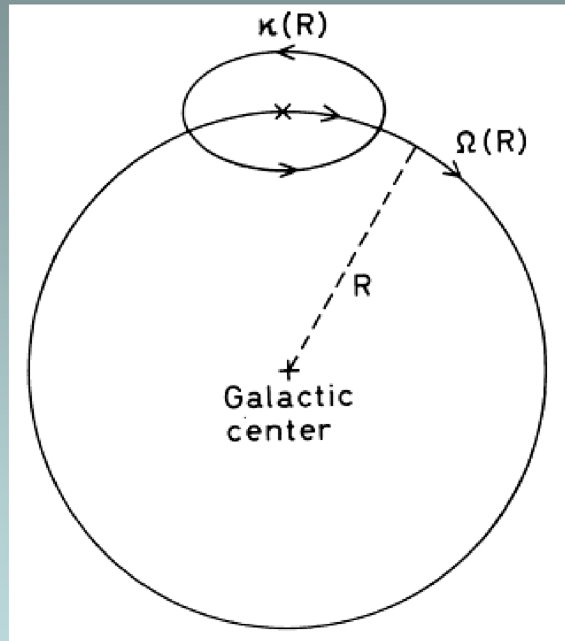


FIG. 1. Angular velocity Ω, epicyclic frequency κ, and related quantities for the 1965 Schmidt model of the Galaxy.



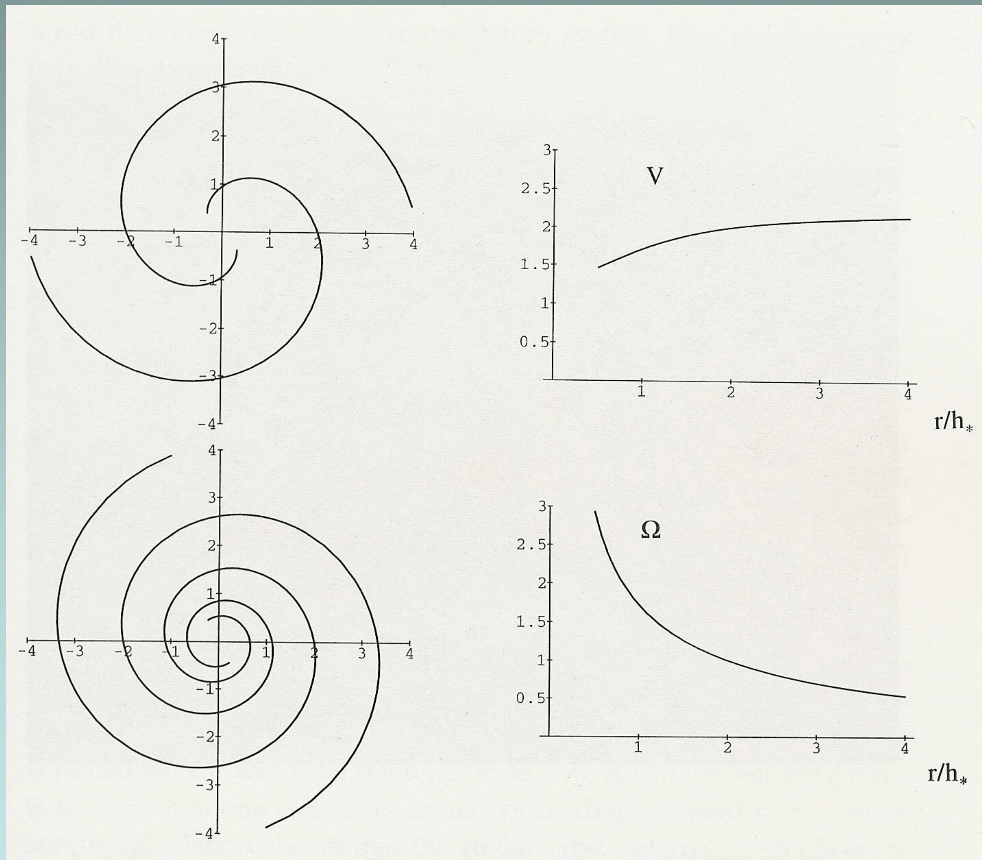
$$\kappa^2 = 4\Omega^2\left(1 + \frac{1}{2}\frac{d\ln\Omega}{d\ln r}\right); \Omega^2 = \frac{1}{r}\frac{d\Phi}{dr}$$

κ epicyclic frequency
Ω differential rotation

(note that, in the 60s, dark halos did not exist!)

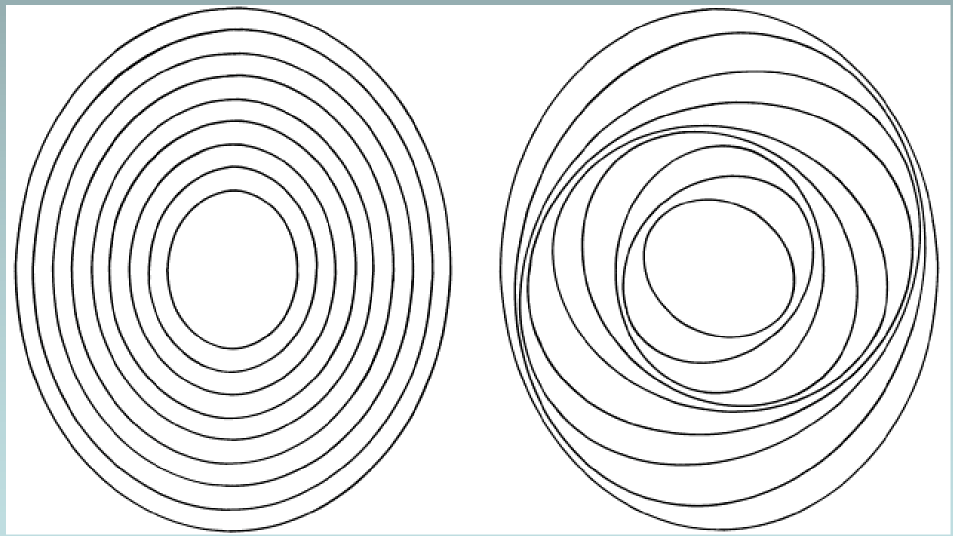
THE WINDING DILEMMA

Differential rotation would rapidly (in a couple of turns) stretch any arm into a tightly wound spiral structure:
How can we reconcile this fact with the observations of so many galaxies with open arms?



LINDBLAD’S KINEMATIC WAVES

B. Lindblad’s kinematic waves: the beginning of the density wave theory



THE PROBLEM OF SPIRAL STRUCTURE (Oort, 1962)

Focus on grand design,
i.e., regular, large-scale spiral structure:

- Primarily gaseous or primarily stellar arms?

- How is spiral structure generated?
- How does it persist?

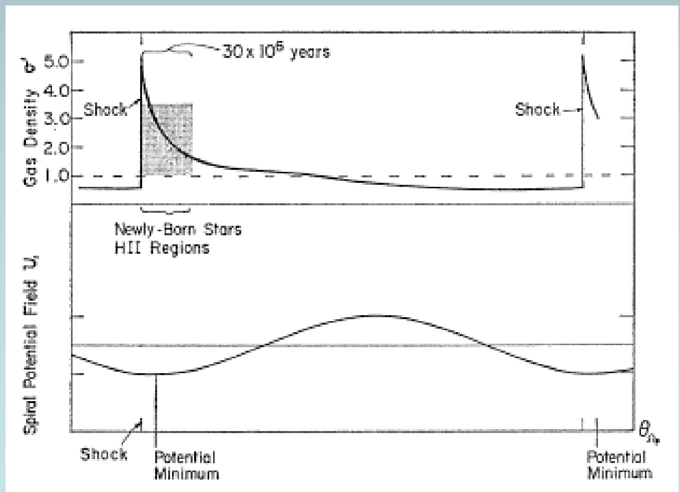
THE PROBLEM OF SPIRAL STRUCTURE

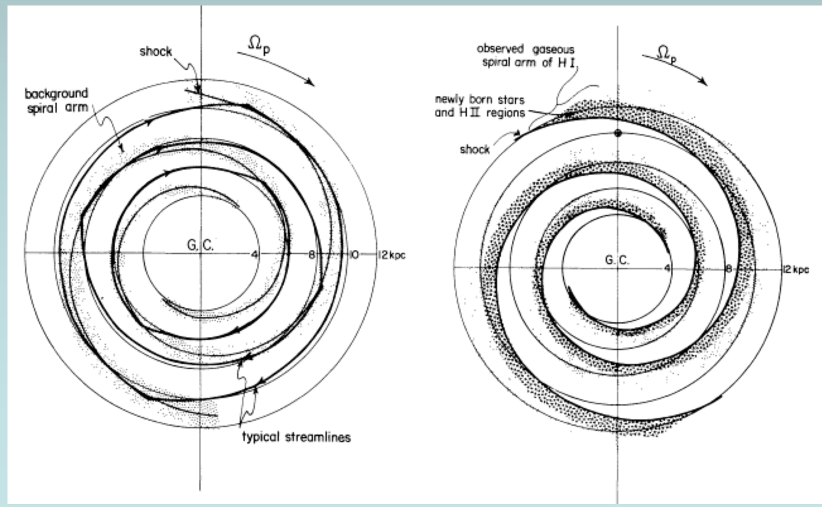
In relation to the large scale:

- **Why certain spirals are barred and others are not?**
- **How do we explain the different degrees of regularity in the observed spiral structure?**
- **How do we explain flocculent spiral structure?**
- **Why trailing structure?**
- **Why is grand-design generally two-armed?**
- **Why do we often see different coexisting morphologies?**
- **How do we explain the Hubble morphological classification?**
- **What sets the amplitude of the observed structure?**

THE SHOCK-WAVE PATTERN

Because the rotation of the disk is differential, a quasi-stationary pattern will be moving supersonically with respect to the interstellar medium over most of the galaxy disk. If its amplitude is large enough, shocks will be generated and these, in turn, will favor star formation.





W.W. Roberts 1969

Visser's study of M81

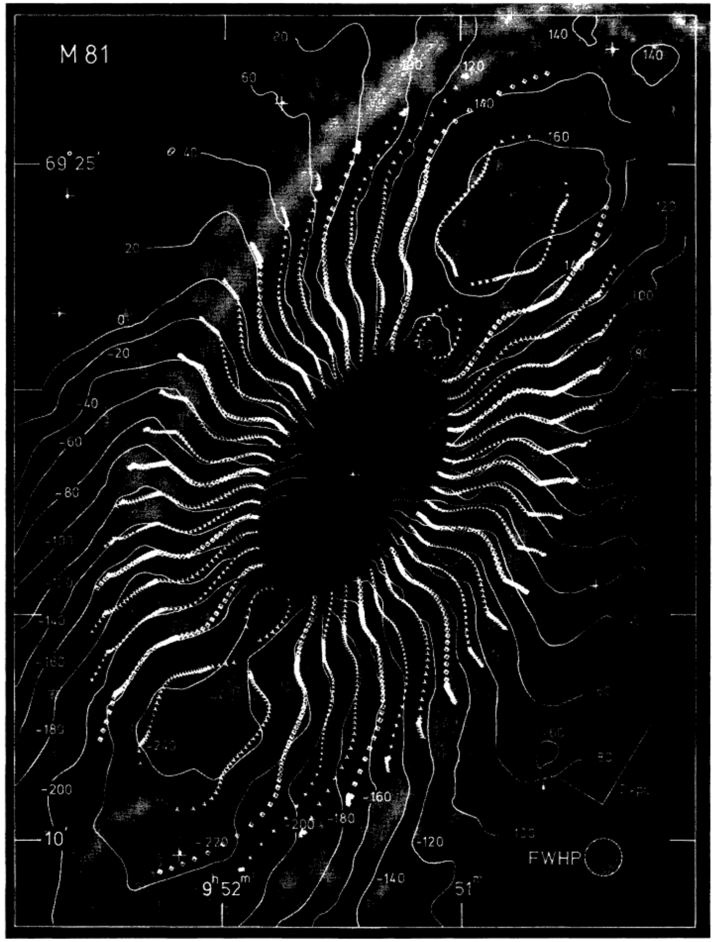
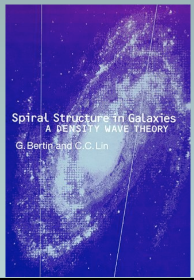


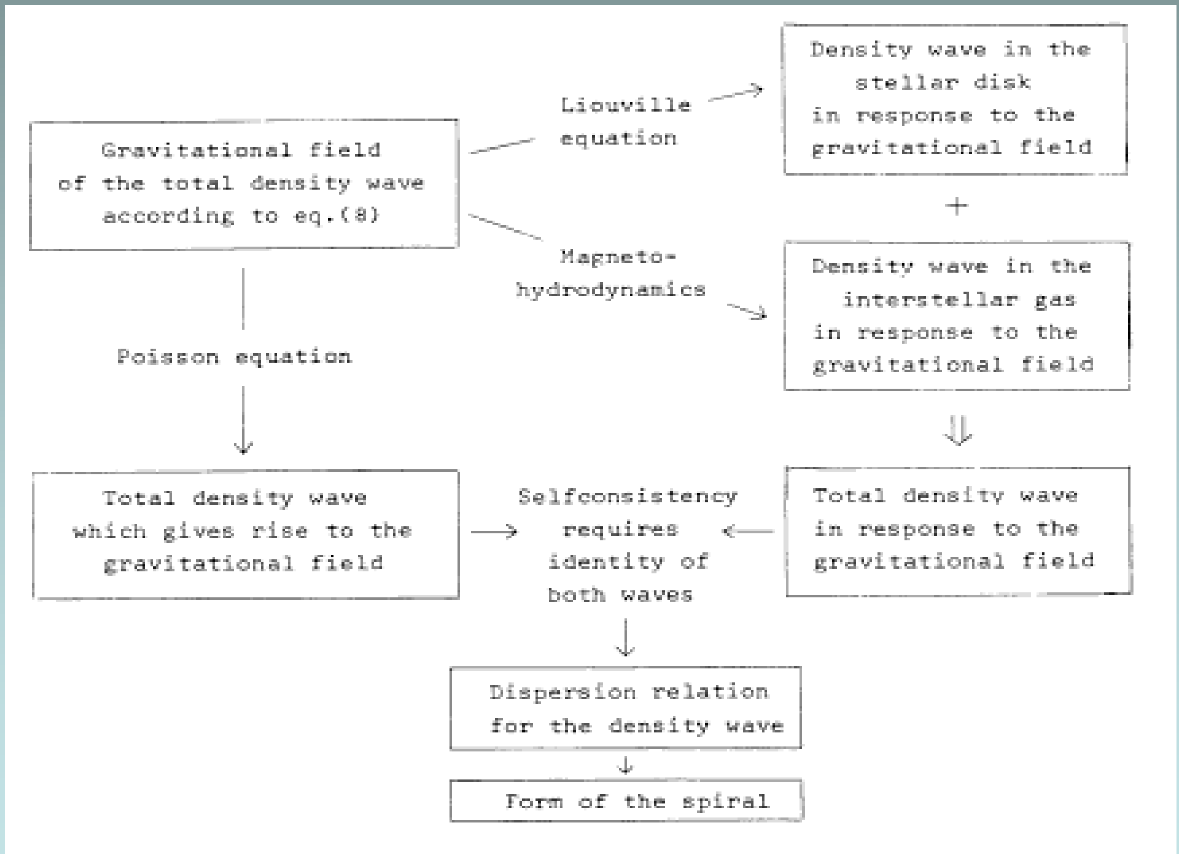
Fig. 5. The radial-velocity field of the final model (symbols) together with the observed velocity field (full and dashed lines) at an angular resolution of 50″, superimposed on a radiograph of the density distribution of the atomic hydrogen at 25″ resolution. See also the caption of Fig. 4

Visser 1980

FOUR DYNAMICAL SCENARIOS

	Quasi-stationary	Rapidly evolving
Internal origin	Discrete spectrum; one or few self-excited modes 	Continuous spectrum, regenerative spiral structure **P.O. Lindblad 1960; Goldreich & Lynden-Bell 1965**
External origin	Discrete spectrum, damped modes. Orbiting satellite?	Continuous spectrum. “One-shot” tidal interactions **A. Toomre 1980**

DENSITY WAVES



Lin & Shu 1964, 1966

DENSITY WAVES IN A THIN FLUID DISK

$$\sigma_1 = \overline{\sigma} \exp[i(\omega t - m\vartheta + \Psi(r))]$$

$$k(r) \equiv \frac{d\Psi(r)}{dr}; |rk| >> 1, m = O(1)$$

Dispersion Relation:

$$(\omega - m\Omega)^2 = \kappa^2 + c^2 k^2 - 2\pi G\sigma |k|$$

Doppler-shifted frequency

Angular momentum conservation

pressure

Jeans

LOCAL STABILITY

Dispersion relation studied as $\omega = \omega(k)$

$$Q = \frac{c\kappa}{\pi G \sigma} \geq 1$$

Condition for local stability against axisymmetric perturbations

For Q < 1, there is a range of wavelengths for which density waves are unstable.

SEMI-EMPIRICAL APPROACH

Dispersion relation studied as $k = k(r;m,\Omega_p)$

m **Number of arms**

$\omega = m\Omega_p$ **Pattern frequency**

By assigning these quantities, under the assumption that spiral structure is quasi-stationary, the dispersion relation is used to determine the pitch-angle of spiral arms:

$$\tan i = \frac{m}{rk}$$

Short-wave-branch.
Empirically, corotation in the outer disk

GROUP PROPAGATION?

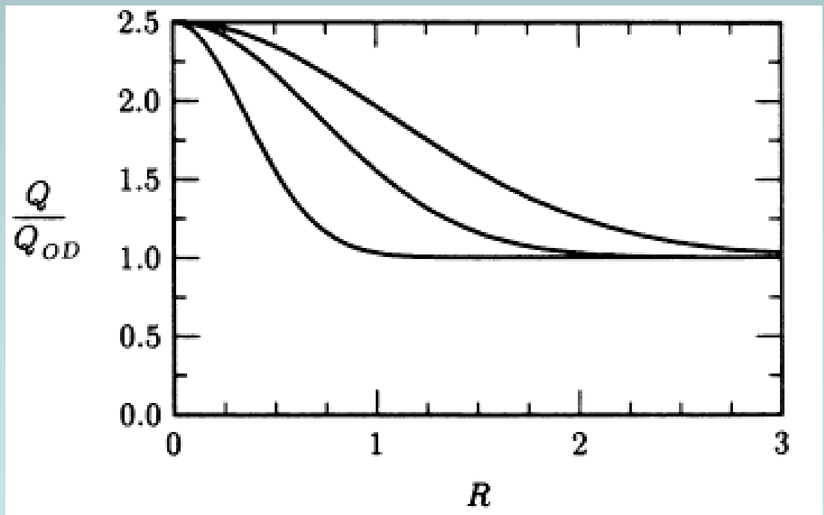
$$c_g = -\frac{\partial \omega}{\partial k}$$

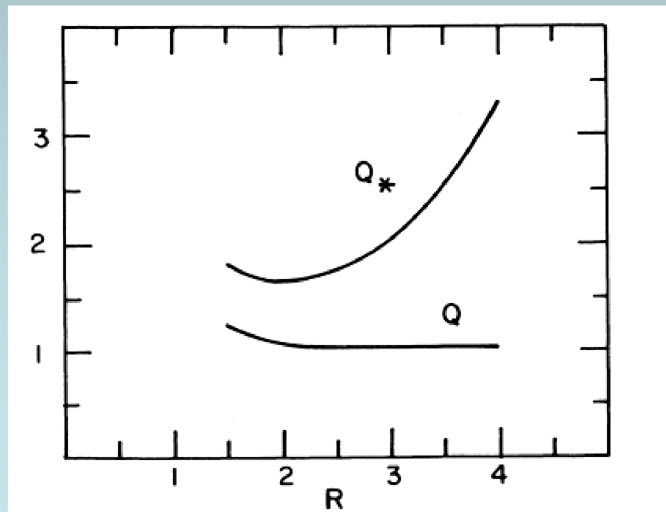
Short waves (used for application to observations) bound to disappear quickly, propagating inwards, in the direction of the galaxy center………

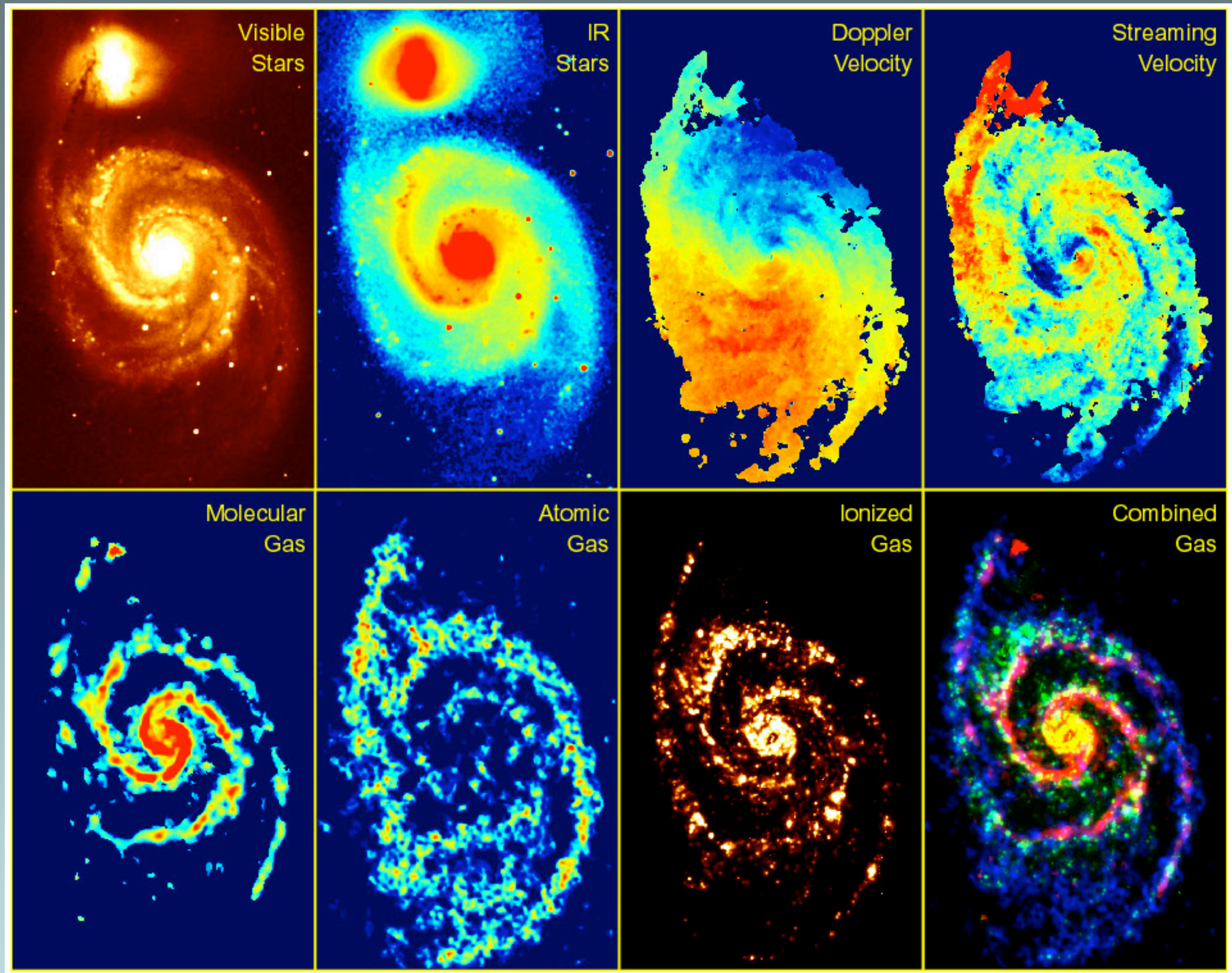
A. Toomre1969

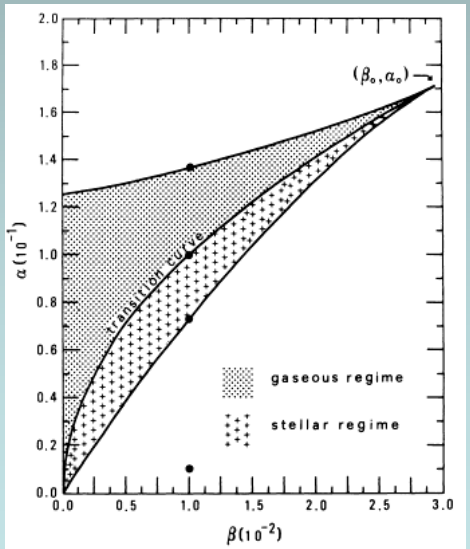
GAS, STARS, SELF-REGULATION

Gas is a cold dissipative component
Gas is diffuse, subject to small-scale spiral activity
A small amount of gas makes the effective Q much smaller than Q_*, fueling Jeans instability
A sufficient amount of gas enforces a "thermostat" (Q close to marginal stability)









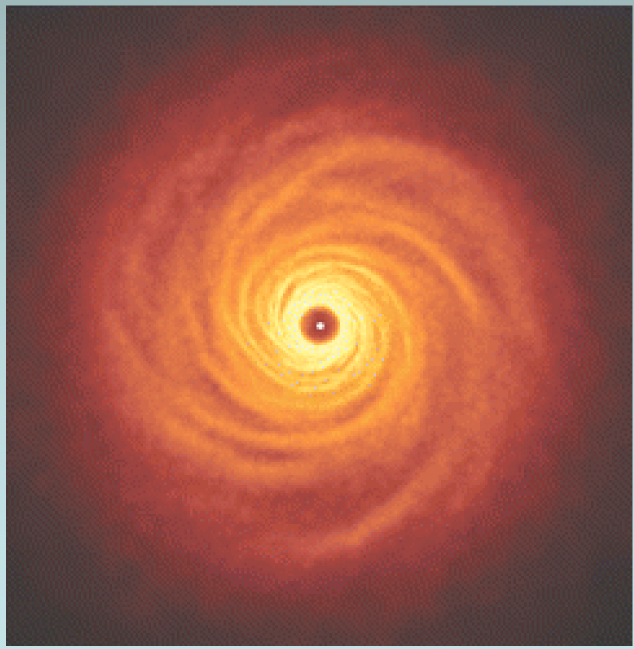
Bertin, Romeo A&A 1988

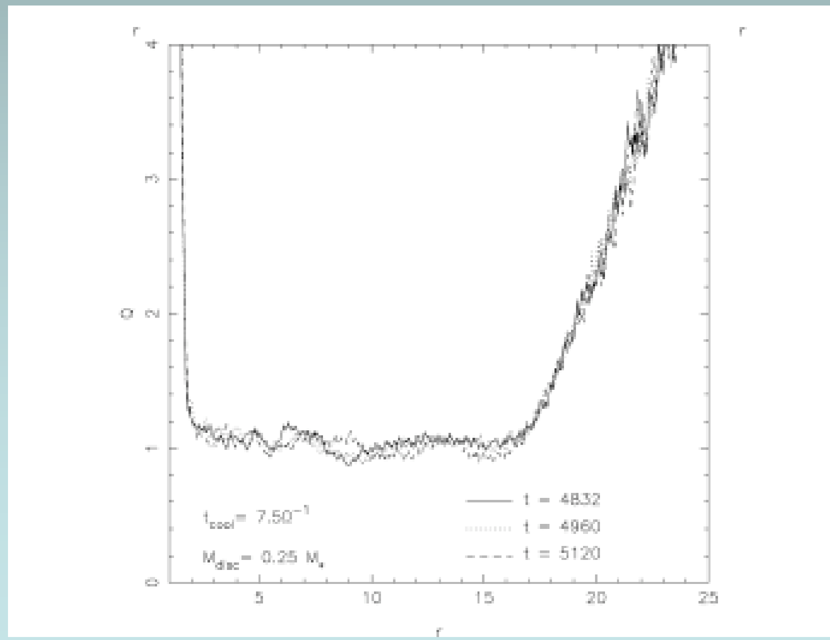
Credits:
CO: BIMA array; S. Vogel, T. Helfer, and BIMA SONG team
Halpha: Palomar Maryland-Caltech Fabry-Perot: S. Vogel, R. Gruendl, R. Rand
IR: Kitt Peak: R. Gruendl, S. Vogel
HI: VLA: A. Rots

Self-regulation for a moderately heavy disk

$M_{disk} = M_{star}/4$

(Lodato & Rice 2004)





<u>ORIGIN OF GLOBAL SPIRAL STRUCTURE</u>
<u>("unstable global modes")</u>

<u>**Feedback**</u> **(density waves refracted back from the galaxy central regions; "Q-barrier")**

+

<u>**Overreflection**</u> **at corotation**

=

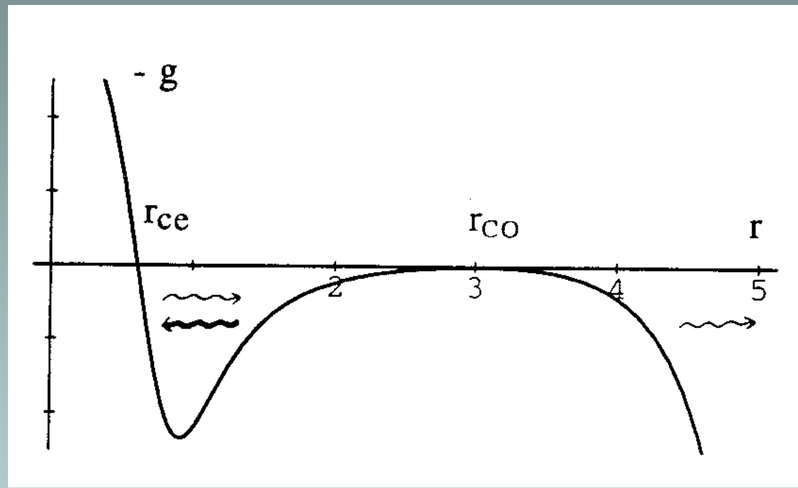
<u>**Global self-excited modes**</u>**, i.e. "standing waves"**
(no radial propagation!)

$$\sigma_1 = \overline{\sigma}(r)\exp[i(\omega t - m\vartheta)]$$

eigenfunction eigenfrequency

A TWO-TURNING POINT PROBLEM (a Schroedinger-type equation)

$$\frac{d^2u}{dr^2} + g(r;\omega)u = 0$$



Boundary conditions:

Outgoing wave (at large radii)
Evanescent wave (at small radii)

Simple turning point at r_{ce} (~ bulge radius) feedback
Double turning point at r_{co} (corotation) overreflection

OVERREFLECTION AND PROPAGATION DIAGRAMS

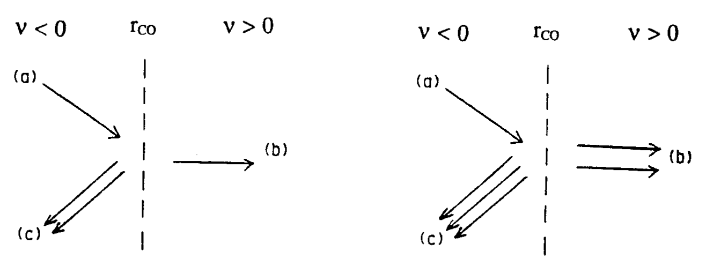


Figure 10.2
Process of overreflection illustrated for two cases of different levels of local stability at corotation. *Left:* Case of local marginal stability (see figure 10.1 or left frames of figures 9.1 and 10.3). *Right:* Case of a system locally unstable at corotation (see middle frames of figures 9.1 and 10.3); for a description, see also the caption to figure 4.1).

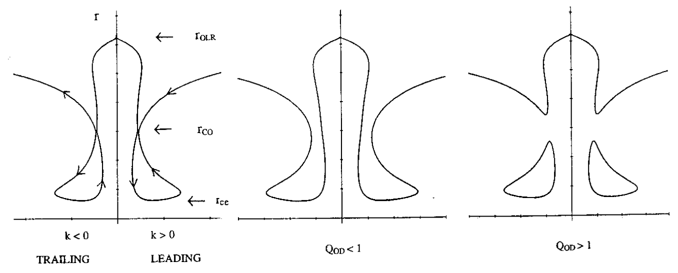


Figure 9.1
Propagation diagrams for the quadratic dispersion relation. The left frame illustrates the properties of the diagram in detail for a model that might support a tightly wound spiral mode. The radial coordinate is on the vertical axis, starting with $r = 0$. The radial wave number k is on the horizontal axis. Note the properties of the wave branches in the vicinity of the marked locations (r_{co}, r_{OLR}, and r_{ce}). Arrows denote direction of group propagation along each wave branch. The middle and right frames illustrate the qualitative change induced in the diagram by changing the value of Q_{OD} below or above the "marginal" value of 1.

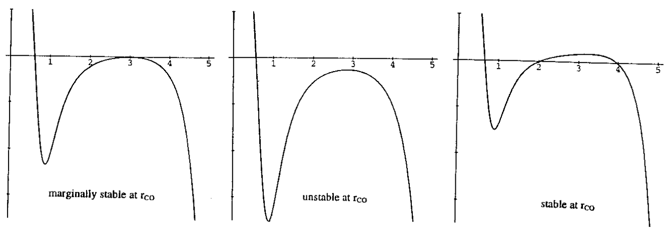


Figure 10.3
Function $(-g)$ can be seen like the potential for a particle with zero energy. The plots given here actually reproduce the function indicated in eq. (10.2) (regime A) for the same models used to draw the propagation diagrams in figure 9.1, following the same sequence from left to right; there is a small difference, in that here the departures from unity of Q_{OD} have been slightly exaggerated, in order to better appreciate the changes induced by modifying the conditions of local stability at corotation ($r_{co} = 3$, as in figure 10.1). This figure can also be used to describe possible cases related to regime B (section 10.2.2).

“RESONANT CAVITY”

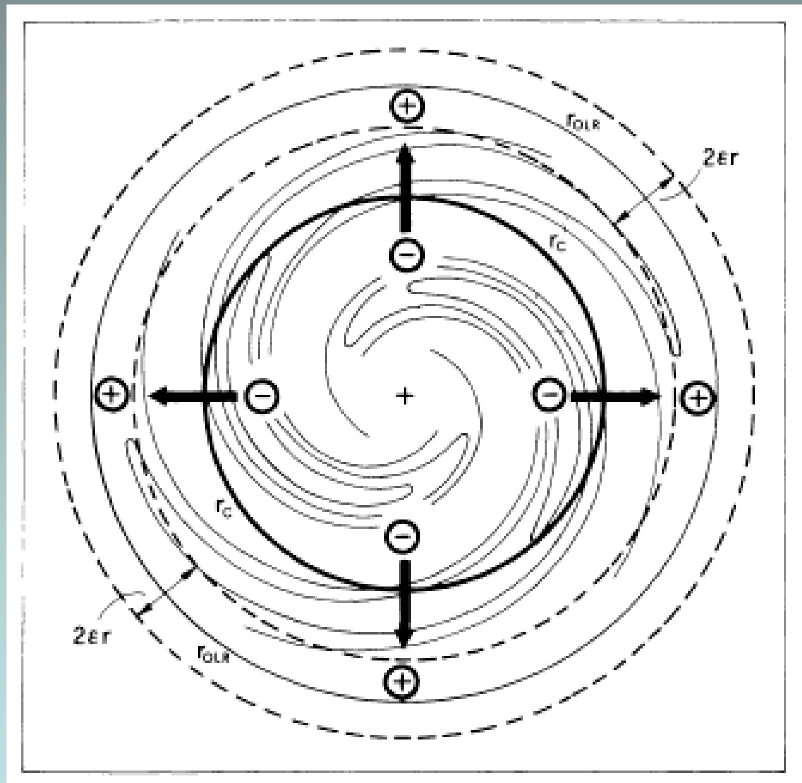
Discrete spectrum, Bohr-Sommerfeld “global Dispersion Relation”

$$\oint k(r;\omega)dr = (2n+1)\pi + i\ln\sqrt{2}$$

$$\oint k(r;\omega_R)dr = (2n+1)\pi$$

$$\gamma \oint \frac{dr}{|\partial\omega / \partial k|} = \gamma\tau = \ln\sqrt{2}$$

ANGULAR MOMENTUM TRANSPORT



Waves have negative energy density inside corotation;
Trailing modes are excited by carrying angular momentum outwards
Normal (Type I) overreflection: long into stronger short wave Mark 1974

CUBIC DISPERSION RELATION

$$\frac{Q^2}{4} = \frac{1}{K} - \frac{1 - \nu^2}{K^2 + J^2/(1 - \nu^2)}, \tag{3.1}$$

where

$$\nu = \frac{(\omega - m\Omega)}{\kappa}, \tag{3.2}$$

$$J = m\epsilon_0 \left(\frac{4\Omega}{\kappa}\right) \left| \frac{d \ln \Omega}{d \ln r} \right|^{1/2}, \tag{3.3}$$

$$Q = \frac{a\kappa}{\pi G \sigma}, \tag{3.4}$$

$$\epsilon_0 = \frac{\pi G \sigma}{r \kappa^2}, \tag{3.5}$$

$$K = 2kr\epsilon_0, \tag{3.6}$$

$$k^2 = k_r^2 + k_\theta^2 = k_r^2 + \frac{m^2}{r^2} = \frac{m^2}{r^2}(1 + \mu^2). \tag{3.7}$$

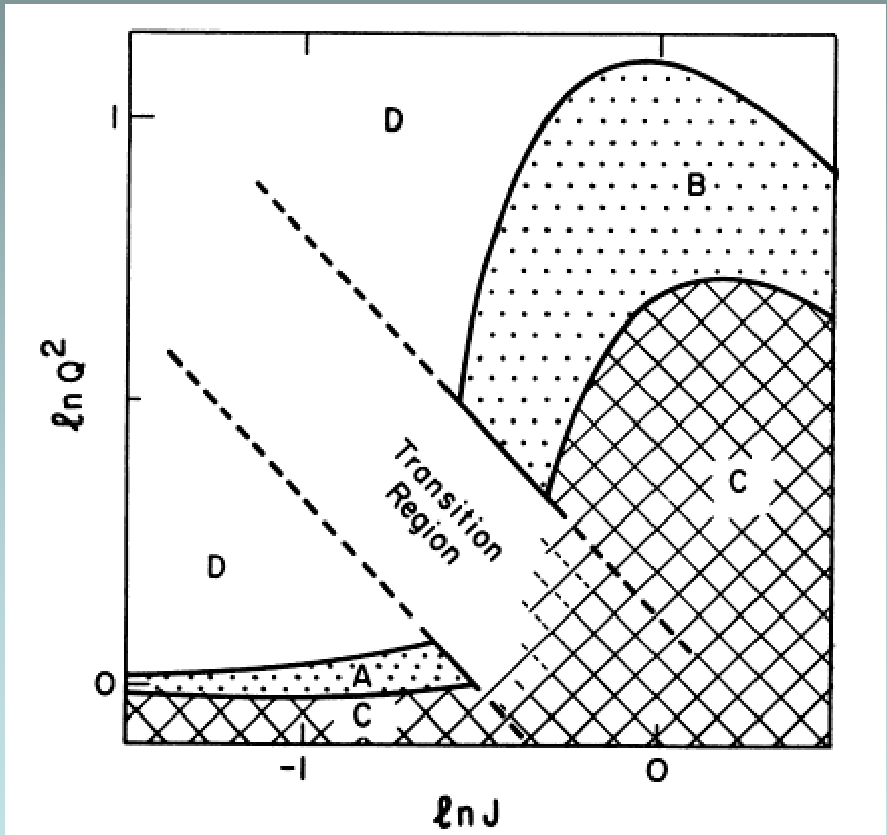
$$\epsilon_0^2 \ll 1,$$

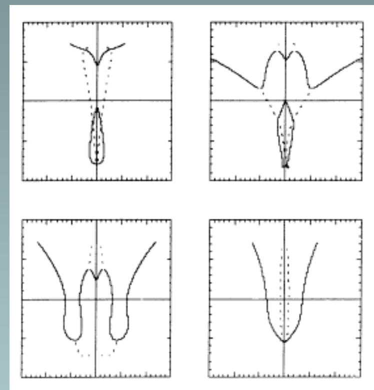
$$K^2 = O(1).$$

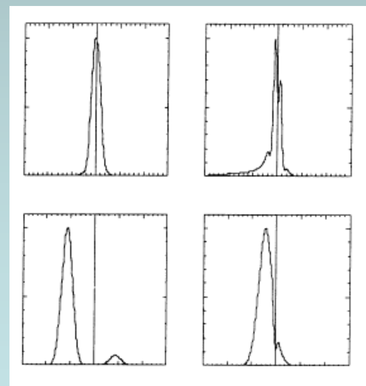
Bertin 1983; Bertin, Lin, Lowe 1984; Bertin, Lin, Lowe, Thurstans 1989

NORMAL AND BARRED SPIRAL MODES

hot







heavy

In region A, Type I overreflection, of long into stronger short trailing wave

In region B, Type II overreflection, of leading into stronger trailing wave

MODE PROTOTYPES

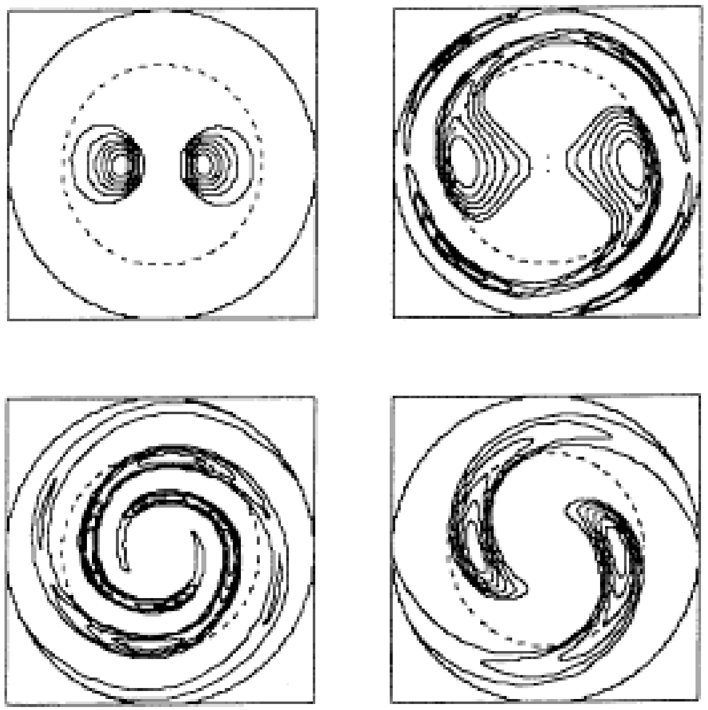
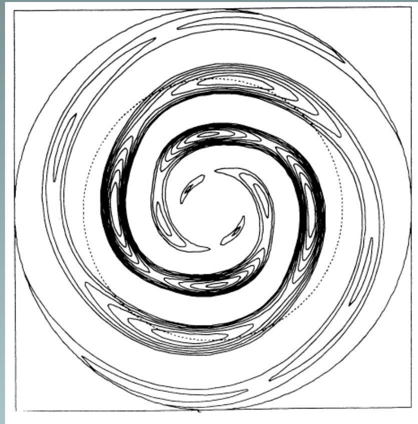
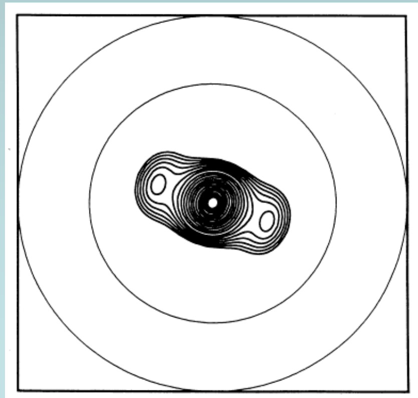


FIG. 11.—Mode prototypes. Four key morphological types are compared: SB0, SB(s), and S, all with moderate growth; a violently unstable S mode at the low right corner. The dynamical properties of these modes are discussed in Paper II.





BARRED MODES, AMPLITUDE MODULATION, COROTATION RADIUS

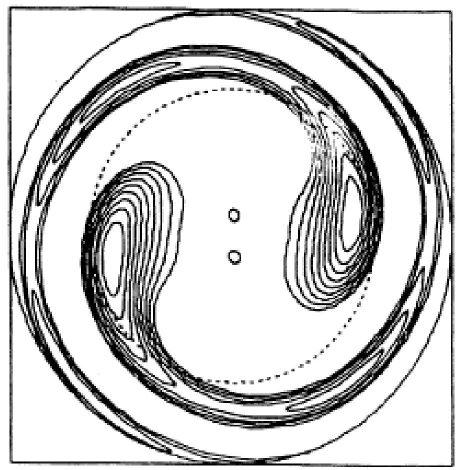


FIG. 1——Positive density contours for a barred mode from the survey reported by Bertin et al. (1989a). The structure of the mode (pitch angle, gaps, and arm shape) closely resembles the barred spiral structure found in NGC 1300 [compare with Fig. 1(f) of Elmegreen et al. 1992a]. The dotted circle is the corotation circle.

THE MORPHOLOGY CLASSIFICATION

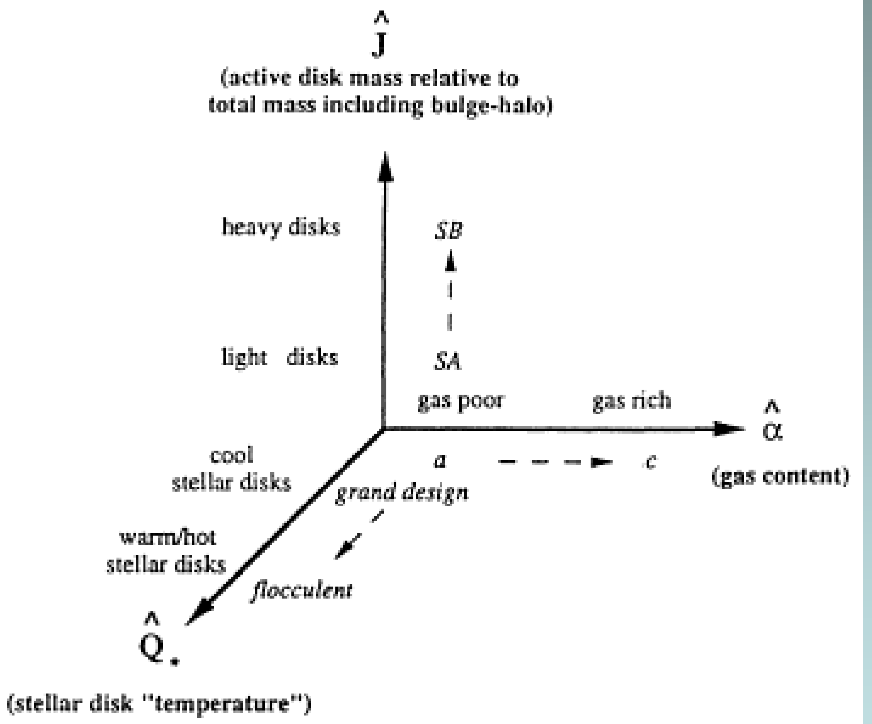


Fig. 1. Framework for the classification of the morphologies of spiral galaxies on the basis of their intrinsic modal characteristics (see Bertin 1991)

K-BAND OBSERVATIONS: THE DECISIVE "PROOF"

Large scale spiral structure is a density wave in the stellar disk.

It is very frequent and generally two-armed.

Even when its amplitude is relatively large, the density perturbation is smooth and sinusoidal, thus the theory of linear modes can be applied to the observed morphologies.

Multiple-armed spiral structure is mostly a Population I phenomenon.

THE PROBLEM OF SPIRAL STRUCTURE (Oort, 1962)

Focus on grand design,
i.e., regular, large-scale spiral structure:

-Primarily gaseous or primarily stellar arms?
grand design arms are primarily stellar

- How is spiral structure generated?
a resonant cavity with overreflection at corotation
- How does it persist?
as a global mode (“standing wave pattern”)

THE PROBLEM OF SPIRAL STRUCTURE (as frequently asked)

Swing "theory" or "modal theory"?

Swing is a mechanism, not a theory. Swing is overreflection of leading into trailing waves; as such, it is automatically incorporated in the modal theory of bar modes. Normal spiral modes are excited by long into short wave overreflection.

The rapidly evolving/external origin scenario (continuous spectrum, no unstable modes, "one-shot" tidal scenario) has not been demonstrated to be viable and is unlikely to be the general explanation of grand design spiral structure.

THE PROBLEM OF SPIRAL STRUCTURE

In relation to the large scale:

- **Why certain spirals are barred and others are not?**
- **How do we explain the different degrees of regularity in the observed spiral structure?**
- **How do we explain flocculent spiral structure?**
- **Why trailing structure?**
- **Why is grand-design generally two-armed?**
- **Why do we often see different coexisting morphologies?**
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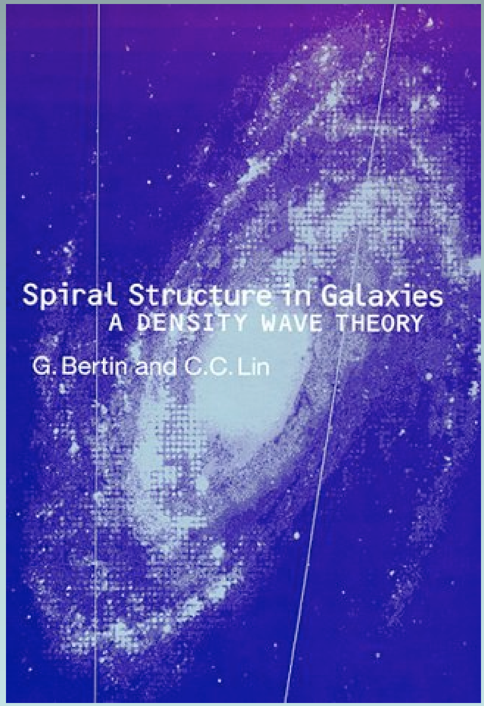
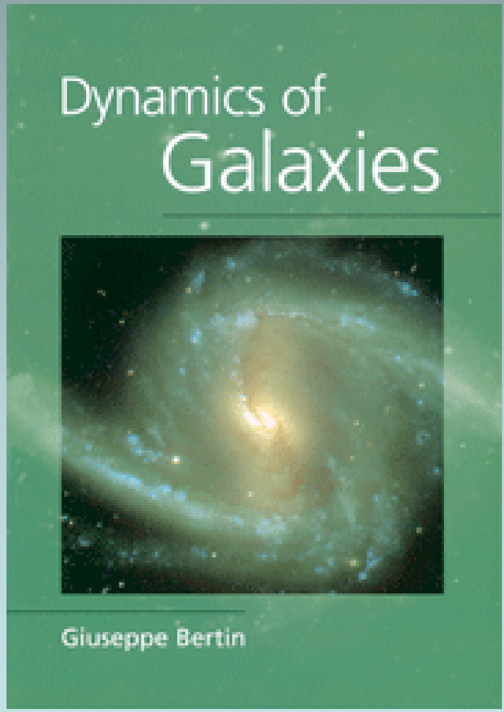
- **What sets the amplitude of the observed structure?**

CONCLUSIONS



The MIT Press, 1996



Cambridge University Press, 2000