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Spiral Modes in Galaxy Disks

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Bibliography

Bertin, G., Lin, C.C. 1996, *Spiral structure in galaxies: A density wave theory*, MIT Press, Cambridge & London

These are lecture notes, intended for distribution to participants.

SPIRAL MODES IN GALAXY DISKS

II A

DENSITY WAVES

Oort: (1962)

"In systems with strong differential rotation, such as is found in all non-barred spirals, spiral features are quite natural. Every structural irregularity is likely to be drawn out into a part of a spiral. But *this* is not the phenomenon we must consider. We must consider a spiral structure extending over the whole galaxy, from the nucleus to its outermost part, and consisting of two arms starting from diametrically opposite points. Although this structure is often hopelessly irregular and broken up, the general form of the large-scale phenomenon can be recognized in many nebulae. I am very well aware that there are many systems to which this general picture does not apply; you have seen quite a number of them in the account given by Mrs. Burbidge, and it is well to keep this, as well as the existence of the large class of barred spirals, constantly in mind. But at the moment I want to concentrate attention on those galaxies in which a more or less continuous pattern of the kind described can be discerned.

flocculent

barred

"It may be practical, at least in the present stage of knowledge, to separate the problem into two parts:

(a) How did the spiral structure originate?

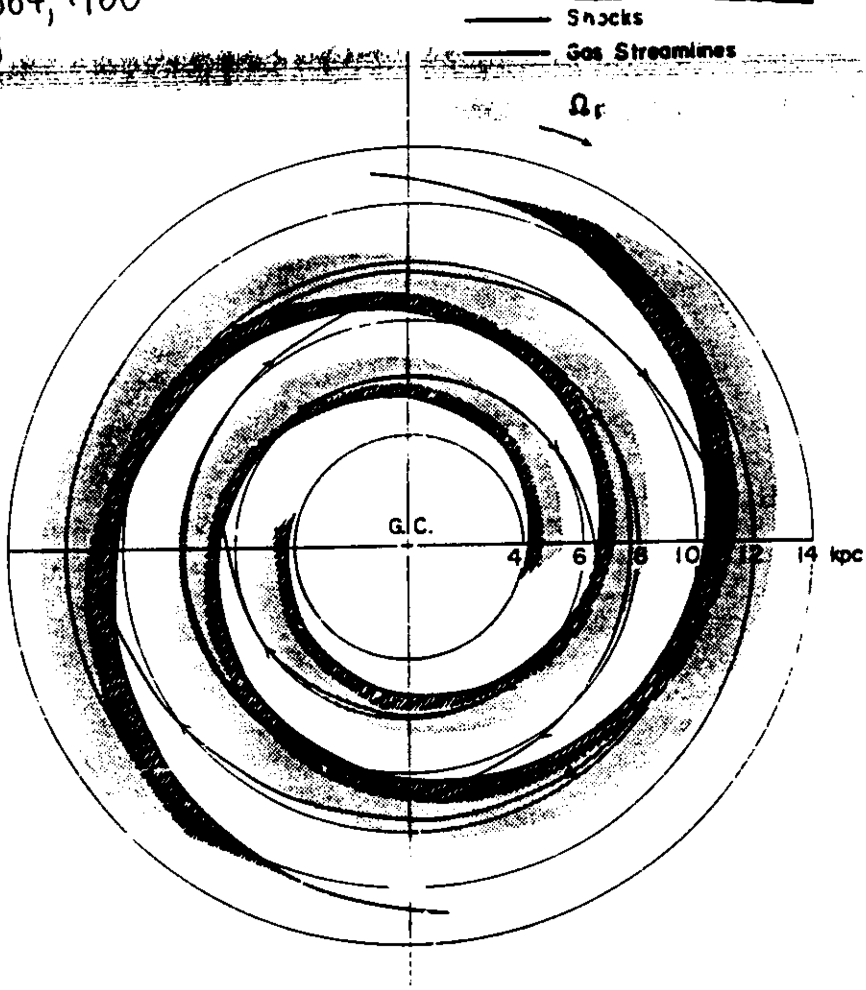
(b) How does it persist once it has originated?

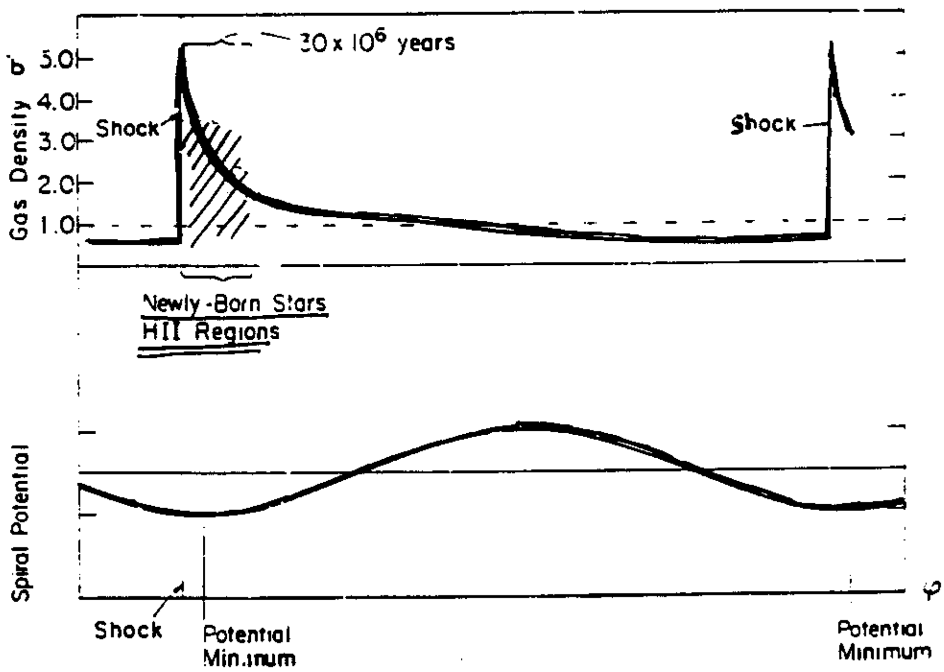
"In this connection an important question is whether the arms in spiral nebulae consist principally of gas or of stars. We know from the 21-cm observations in the galactic system, as well as from numerous data on other systems, that the interstellar gas is concentrated in the arms. But we do not know with any certainty whether or not *stars* contribute in an important measure to the mass of the arms. This, however, is one of the few questions concerning spiral structure which could be answered by observations, viz., by photometry of spiral galaxies in different colors."

cf. Schweizer

"Standing wave"
(for LARGE SCALE Structure)

— Lin & Shu 1964, 1966
— Roberts 1969

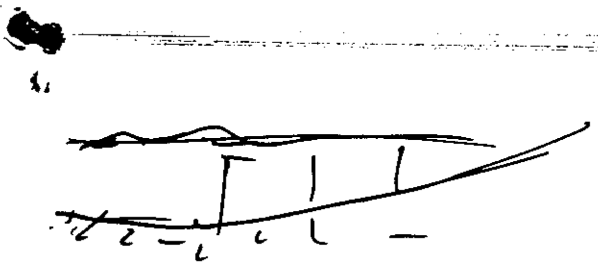




"OPTICAL"

"NEAR INFRARED"
90's

D. Roberts Ph.D. Thesis (1969)



Can we try an <u>approximate</u> description in terms of "waves" ?

$$\frac{d}{dr} \rightarrow k$$

(Note : if $\sigma_1 \sim e^{ikr}$, $\frac{d}{dr}\sigma_1 \sim ik\, e^{ikr} = ik\sigma_1$)

(as in WKB)

?

N.B. In a sense, this is how it all started!
(Lin & Shu 1964)

III^{bi} (b) DENSITY WAVES

The Dispersion Relation for density waves on a zero-thickness, axisymmetric disk of stars, in the limit: $|rk| \gg 1$, $|m/rk| \ll 1$

is (Lin & Shu 1964, 1966) $\exp\left[i\left(\omega t - m\vartheta + \int k\,dr\right)\right]$

$$\frac{k_0}{|k|} = \frac{1}{x}\left[1 - \frac{\nu\pi}{\sin\nu\pi}\,\mathcal{G}_\nu(x)\right] = -2\,\frac{e^{-x}}{x}\sum_{n=1}^{\infty}\frac{I_n(x)}{\left(\frac{\nu}{n}\right)^2 - 1} \Longleftarrow$$

$$\nu = \frac{\omega - m\Omega}{\kappa}\ ; \quad k_0 = \frac{\kappa^2}{2\pi G\sigma}\ ; \quad x = \frac{k^2 c_r^2}{\kappa^2}$$

$$\mathcal{G}_\nu(x) = \frac{1}{2\pi}\int_{-\pi}^{\pi} d\varphi\,\cos(\nu\varphi)\,e^{-x(1+\cos\varphi)}$$

cf. Bernstein 1958
Lin & Shu, Brandeis Lectures 1968

One-component zero-thickness fluid model is a simple, useful <u>tool</u>

(cf. detailed discussion at IAU 146)

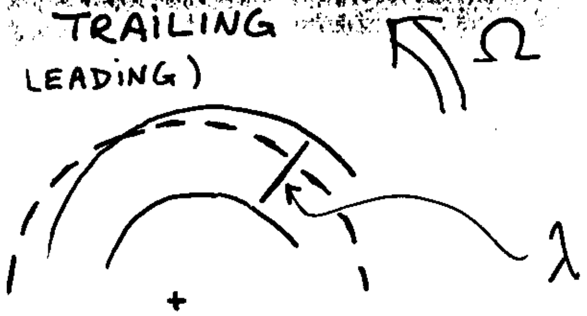
Appropriate choice of basic state functions $\sigma(r)$, $c(r)$ and of boundary conditions can be adjusted to match the physical requirements of realistic disks (gas, stars, 3D)

- active disk mass
- self-regulation

APPROXIMATE SOLUTIONS

m = number of arms

$k<0$ TRAILING
($k>0$ LEADING)



$$k_{TOT}^2 = k^2 + \frac{m^2}{r^2}$$

$$k = \frac{2\pi}{\lambda}$$

$\boxed{r^2 k_{TOT}^2 \gg 1}$ $\Longrightarrow$ LOCAL ANALYSIS ALLOWED FOR POTENTIAL THEORY (relation between σ_1 and Φ_1)

EQUATIONS OF THE MOTION FOR FLUID MODEL GIVE ANOTHER LOCAL RELATION BETWEEN σ_1 and Φ_1

$\varepsilon_0 = \pi G \sigma / r\kappa^2 \ll 1$, simplifications cf. Lau Bertin 197.

LOCAL DISPERSION RELATION:

$$\boxed{\frac{Q^2}{4} = \frac{1}{K} - \frac{(1-\nu^2)}{K^2 + \frac{J^2}{(1-\nu^2)}}}$$

Ap.J. 1989
338, 104

$K \equiv 2\varepsilon_0 r |k_{TOT}|$

$\nu \equiv (\omega - m\Omega)/\kappa$

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

$J = 2m\varepsilon_0 (2\Omega/\kappa) |d\ln\Omega / d\ln r|^{1/2} = \frac{\sigma}{\bar{\sigma}}$

$J \sim 10^{-10}$ for planetary rings

$\pm$

$J \to 0$ WKB

small epicycles

EXAMPLE

(1 component, fluid model, tightly wound waves)

inertia — ang. mom. — "sound" — self-gravity

$$\underbrace{m^2\left(\frac{\omega}{m} - \Omega(r)\right)^2 = \kappa^2(r)}_{\text{Lindblad's dispersion orbits}} + k^2 c_s^2(r) - 2\pi G\sigma(r)|k|$$

local rotation — epicyclic frequency — velocity dispersion — disk density

"BASIC STATE"

$k = \frac{2\pi}{\lambda}$

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

number of roots for k

$e^{\gamma t}$

<u>N.B.</u> The local D.R. can be studied in a "reverse" manner, to judge <u>local stability</u>, by looking at the allowed ω's for given k. The above example gives essentially <u>Toomre's axisymmetric stability criterion</u>:

For $m=0$, $\omega^2 > 0$ for any k if

$$Q \equiv \frac{c_s \kappa}{\pi G \sigma} \geq 1$$

local stability

FROM LOCAL D.R. $\mathcal{D}(\omega, m, k; r) = 0$

ONE DERIVES BASIC INFORMATION:

1) MARGINAL STABILITY CURVES $(\nu^2 = 0)$

2) WAVE BRANCHES & <u>PROPAGATION DIAGRAMS</u>
(for $\underline{\Omega_p}$ assumed, in a given basic model $\underline{k = k(r)}$)

3) GROUP VELOCITY c_g $(\partial\omega/\partial k)$

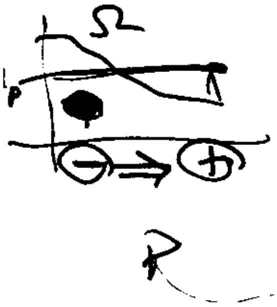
$Q = Q(r)$
$J = J(r)$

4) WAVE ACTION $\mathcal{A} = (\partial\mathcal{D}/\partial\omega)\, a^2$

5) ANGULAR MOMENTUM $\mathcal{J} = m\mathcal{A}$

6) ENERGY $\mathcal{E} = \omega\mathcal{A}$ $E = \hbar\omega$

7) FLUX $\mathcal{F} = c_g\mathcal{A}$



<u>note:</u> $\mathrm{sgn}(\mathcal{A}) = \mathrm{sgn}(\nu)$ — negative for $r < r_{co}$; positive for $r > r_{co}$

$$\nu = \frac{(\omega - m\Omega)}{\kappa} = \frac{m(\Omega_p - \Omega)}{\kappa}$$

$$\Omega_p = \mathrm{Re}(\omega)/m$$

II B

SPIRAL MODES

but <u>where is corotation</u> ?

i.e., what determines the pattern speed $\frac{\omega}{m}$?

$\Rightarrow$ DISCRETE SELF-EXCITED GLOBAL SPIRAL MODES

Lau, Lin, Mark 1976 ; Bertin, Lau, Lin, Mark, Sugiyama 1977

Now (work done in the 80's) a reasonable <u>physical</u> picture has been proposed, and we can tell why some galaxies are <u>barred</u> (heavy disks, passive gas), others are <u>non-barred</u> (light disks, active gas), and others do not show any significant large scale spiral structure

Bertin & Lin 1995, MIT Press
"SPIRAL STRUCTURE IN GALAXIES: A Density Wave Theory"

"LOCAL" DISPERSION RELATION, *PROPAGATION*

$k = k(r)$

$$\boxed{\begin{array}{c}\omega = \omega(k, r)\\ \partial\omega / \partial k = c_g\end{array}}$$

group velocity

WAVES PROPAGATING IN OPPOSITE DIRECTIONS

$m\mathcal{A} = \mathcal{J}$

$\omega\mathcal{A} = \mathcal{E}$

but large scale structures "see the boundaries"......

church bells, violin strings

STANDING WAVES, GLOBAL MODES

$$\boxed{\sigma = A(r)\cos[\,\psi(r) + \omega t - m\theta] \;;\; \Omega p = \mathrm{Re}\,(\omega / m)}$$

"pattern" frequency

EACH GLOBAL MODE CORRESPONDS TO A STANDING WAVE THAT ROTATES RIGIDLY AROUND THE GALAXY AT FREQUENCY Ωp. EACH MODE IS IDENTIFIED BY THE EIGENFUNCTION ($A(r)$, $\psi(r)$) AND BY THE EIGENVALUE (ω) OF THE LINEARIZED EQUATIONS.

- "modes" ~ "standing waves"

GIVEN PATTERN FREQUENCY Ω_p

- modes → damped linear theory: $e^{-\gamma t}$
  → self-excited linear theory: $e^{+\gamma t}$

- modes: modulation
  (nodes for standing waves)

- modes: give the trend for a transition process inherently NON-LINEAR
  cf $m=2$ modes
  Maclaurin (axisym.) → Jacobi (triaxial)

Galaxies are inhomogeneous!

The role of (radial) inhomogeneities is easily incorporated in the standard approach to dispersive systems.

- A first step is that of considering the radial dependence of the quantities entering the basic Dispersion Relation; in particular, one has to make realistic choices for the various parameter profiles characterizing the basic state (e.g., $Q = Q(r)$)

- Then, each allowed wave branch on the *propagation diagram* $k = k(r)$ is associated with given properties for group propagation, energy density, angular momentum density, action flux, etc.

- At special locations in the disk the inhomogeneous system may give rise to *resonances* or to *turning points* (either orbital resonances or locations where wave branches may merge). Of special importance is the corotation radius r_{co}, where $\omega - m\,\Omega(r_{co}) = 0$, which is bound to be the location where waves are excited

- Especially at these locations, or, in general, in order to avoid the limitations of the algebraic WKB description, one can take a step back: $\boxed{k \rightarrow -i\,\partial / \partial r.}$ There is no problem to match the solutions across turning points and to include the role of resonances, where desired.

  $\frac{e^{ikx}}{\sqrt[4]{k}}$

- A discussion of the inhomogeneous problem, possibly directly on a *differential equation*, supplemented with the relevant *boundary conditions* can lead to a proper understanding of the global modes

---

A *slab model* of the corotation region, which correctly captures some of the important *local* instability mechanisms (the so-called *homogeneous shearing sheet*, see Goldreich & Lynden-Bell 1965), considers instead a sort of "time-dependent wavenumber representation". This became very popular, and at one point became also fashionable in the context of *ballooning modes*. For the e.m. plasma case great attention has been placed on the problem of a proper *matching* with the outer equations (see Pegoraro & Schep 1986). In the context of galaxy disks, such slab model has become very misleading, since the problem of matching with the inhomogeneous disk is often ignored and remains, to my knowledge, unresolved.

leading, trailing, short, long

For a differentially rotating thin disk:

$\sim \exp[i(\omega t - m\theta)]$

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

circular rotation frequency

epicyclic frequency

surface mass density

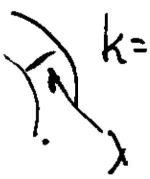
"sound speed"

radial wavenumber

$\frac{m}{r}$ azimuthal wavenumber

$\mathrm{Tan}\, i = \frac{m}{rk}$

inclination of spiral arms



$k = \frac{2\pi}{\lambda}$

$\Omega_p = \omega/m$

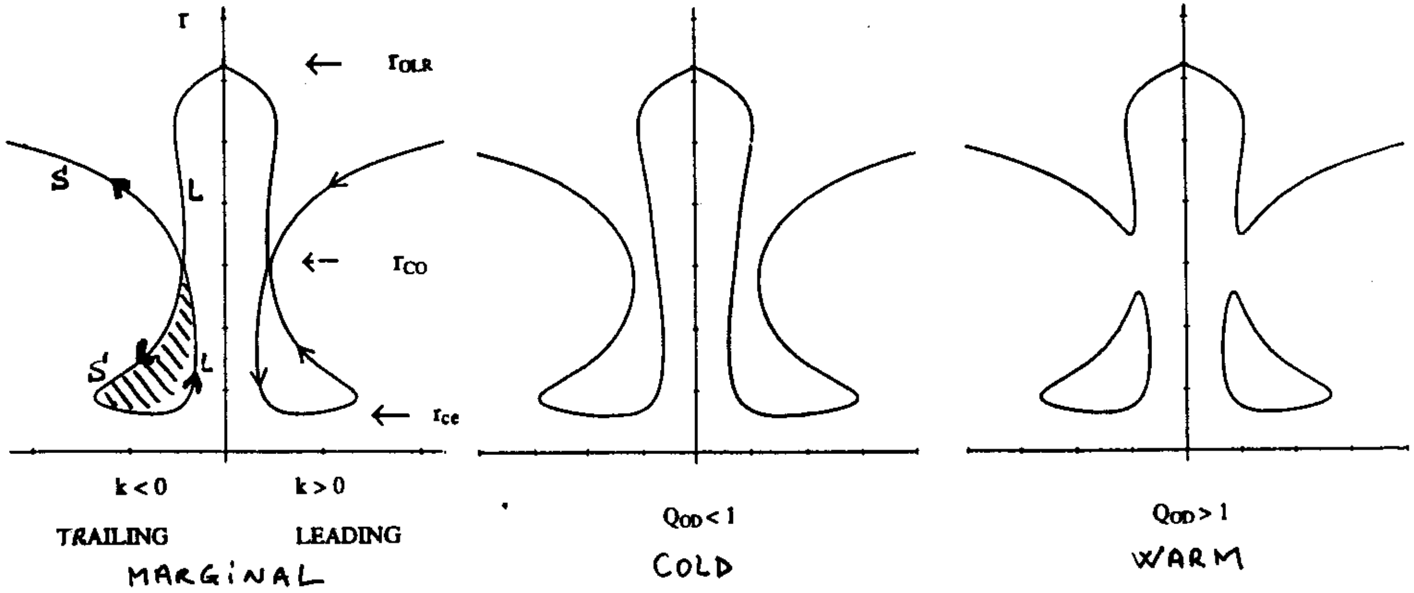
inertia $\sim$ ang. momentum + sound + self-gravity

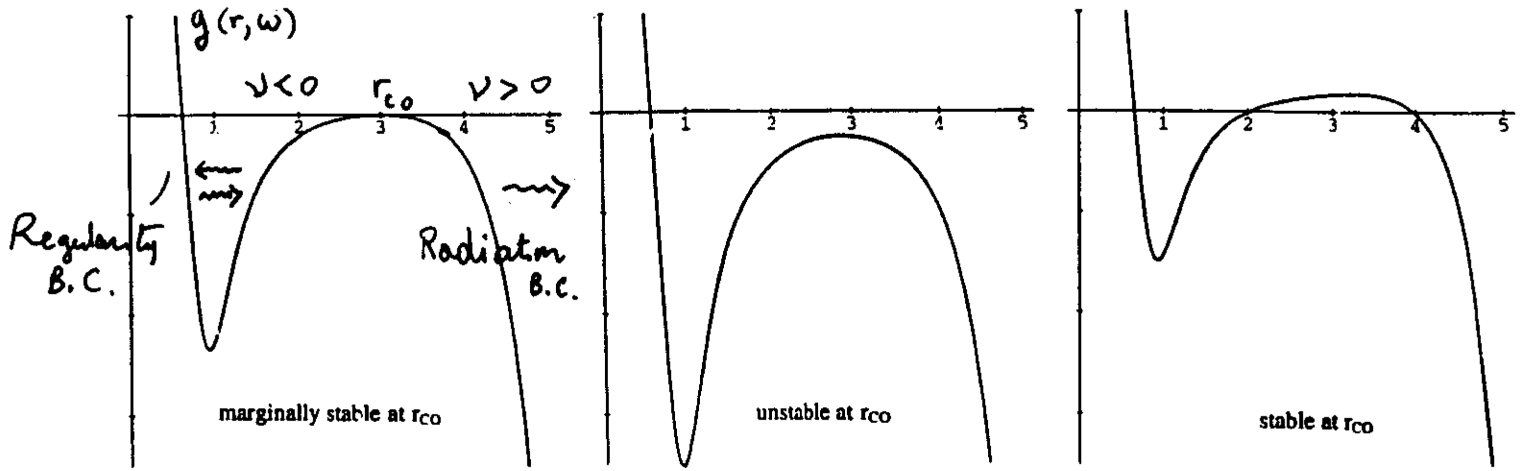
Dimensionless form:

$$\nu^2 = 1 + \frac{1}{4} Q^2 \hat{k}^2 - |\hat{k}|$$

marginal stability $\nu = 0$ $\Longrightarrow$ $\boxed{Q = \frac{c\kappa}{\pi G\sigma}}$

$J = 0$



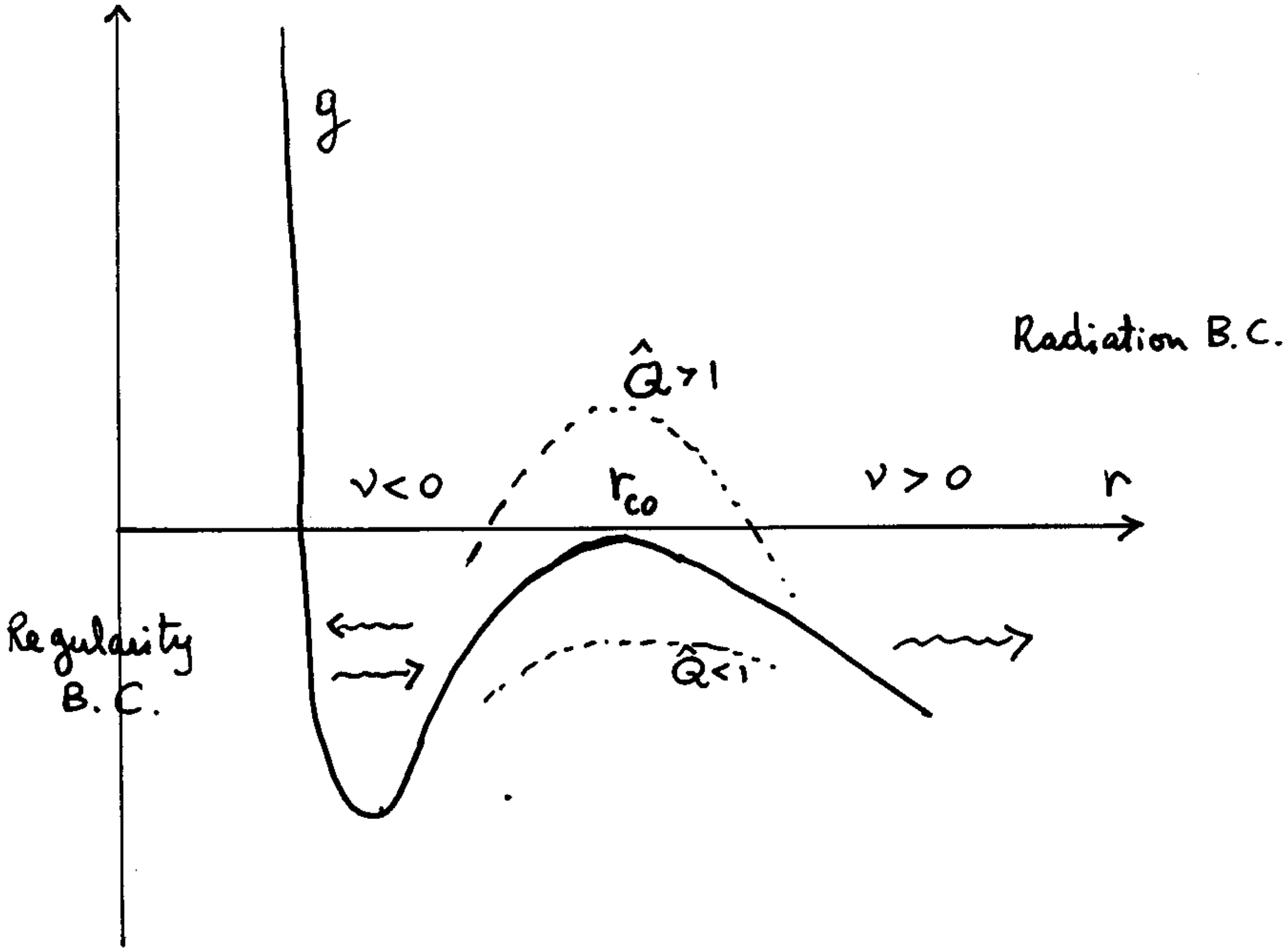


$$u'' - g(r,\omega)\,u = 0$$

DISCRETE SPECTRUM OF GLOBAL SPIRAL MODES

The disk can be "locally" stable everywhere but "globally" unstable

local marginal stability

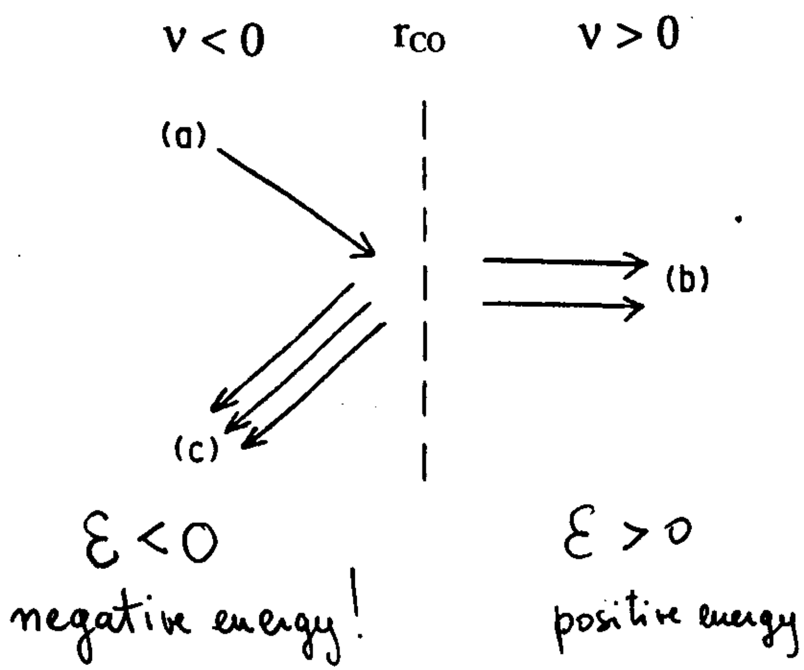


$$u'' - g(r,\omega)u = 0$$

$\pm\sqrt{-g(r,\omega)}$ → TYPE A: long/short trailing, $\hat{Q}=Q$

$\pm\sqrt{-g(r,\omega)}$ → TYPE B: leading/trailing

$J = O(1)$ $\quad J > .6$



OVER-REFLECTION AT COROTATION

Type A	(a)	long trailing wave
	(b)	short trailing wave
	(c)	short trailing wave
Type B	(a)	open leading wave
	(b)	open trailing wave
	(c)	open trailing wave

Under the ordering

$$\left| r\frac{d}{dr} \right| = O(\varepsilon^{-1}) \quad \text{"tightly wound spirals"}$$

$$\varepsilon = \frac{c}{r\kappa} \ll 1 \quad \text{"small epicycles"}$$

we obtain

$$\frac{d^2u}{dr^2} + \frac{1}{r^2\varepsilon^2(r)} \left\{ \frac{1}{Q^2} - 1 + \nu^2 + i\,O(\varepsilon) + O(\varepsilon^2) \right\} u = 0$$

where u is defined in terms of the enthalpy perturbation h_1 as

$$u_1 = h_1 \exp\left[\frac{1}{2} \int (A - i s_k \Sigma)\, dr \right] = h_1 \left[\kappa^2(1-\nu^2)/r\sigma \right]^{-1/2} \exp\left[-i s_k \int \frac{\Sigma}{2}\, dr \right]$$

Note that the common wavenumber $k_0 = s_k \frac{\Sigma}{2}$ is subtracted out. Thus we are focusing on either leading or trailing waves and the ODE for u describes short & long waves (within each type)

$\hat{Q} = 1$

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

$\omega = \omega_R + i\gamma$ $\qquad\qquad$ $\gamma \ll \omega_R$

$$k = k(\omega_R, r) + i\left(\frac{\partial k}{\partial \omega}\right)_{\omega_R}\gamma$$

$$\oint k_R\,dr = (2n+1)\pi \longrightarrow \omega_R = \omega_n$$

"overreflection"

$$\gamma\tau = \frac{1}{2}\ln 2$$

$$\tau \equiv \oint \frac{dr}{c_g} \qquad\qquad c_g = \frac{\partial\omega}{\partial k}$$

$$\oint \frac{\partial k}{\partial \omega}\,dr$$

gain per wave cycle

$e^{(i\omega t)}$

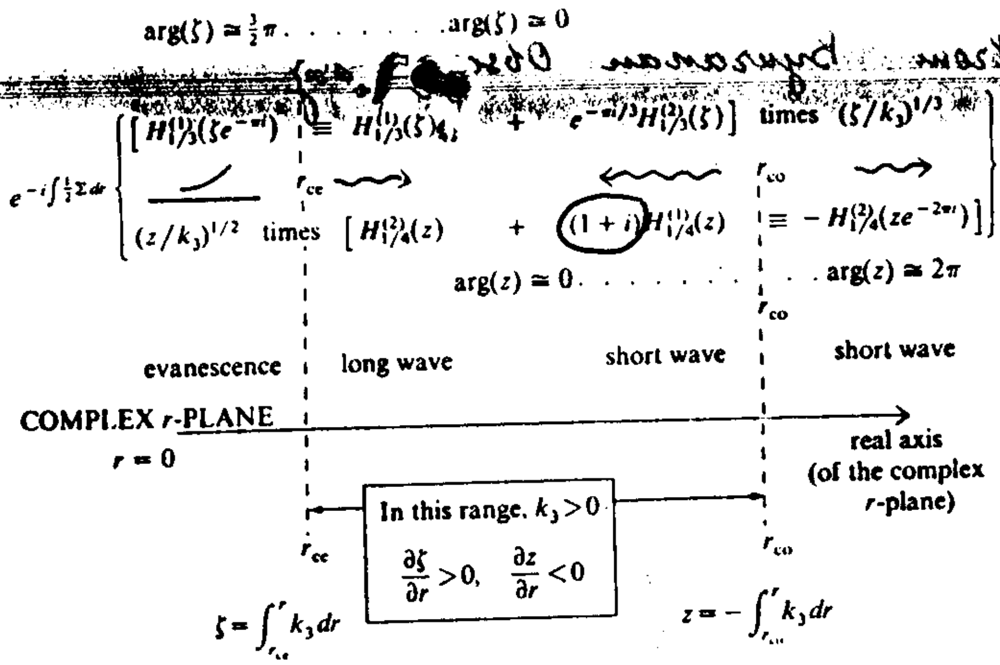
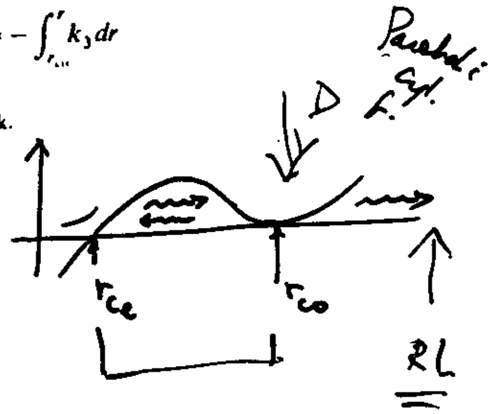


Figure 12. Progressive waves in a galactic disk.

$$u'' + k_3^2(r,\omega)\,u = 0$$



$$(Q=1) \Longrightarrow \quad e^{i\pi} = \sqrt{2}\,\exp\left\{2i\int_{r_{ce}}^{r_{co}} k_3\,dr\right\}$$

OVERREFLECTION

$$\longrightarrow \quad \int_{r_{ce}}^{r_{co}} k_3\,dr = \left(n+\frac{1}{2}\right)\pi + \frac{1}{4}\,i\ln 2$$

$$\int dr$$

$$k_3 = k_3(\omega_R, r) + i\left(\frac{\partial k_3}{\partial \omega}\right)_R \gamma$$

$$|\gamma| < |\omega|$$

GLOBAL DISPERSION RELATION

$$\boxed{\begin{aligned} &\oint k_{3R}\,dr = (2n+1)\pi \\ &\gamma\tau = \frac{1}{4}\ln 2 \\ &\tau = \int_{r_{ce}}^{r_{co}} \frac{dr}{|c_g|} \end{aligned}}$$

← area inside the prop. diagram

$$\omega = \omega_R + i\gamma$$

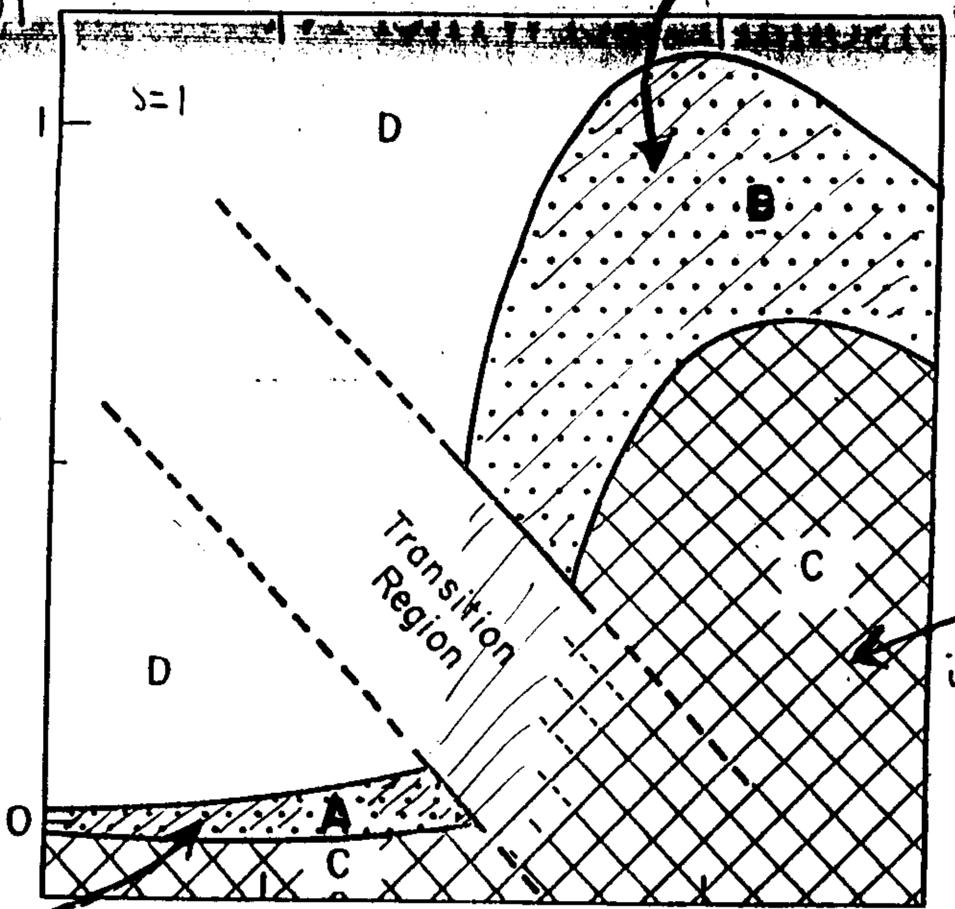
$$e^{\gamma t}$$

MODERATE GROWTH STRIP IN PARAMETER SPACE

moderate growth

$1/Q \sim$ equivalent acoustic speed

NOT

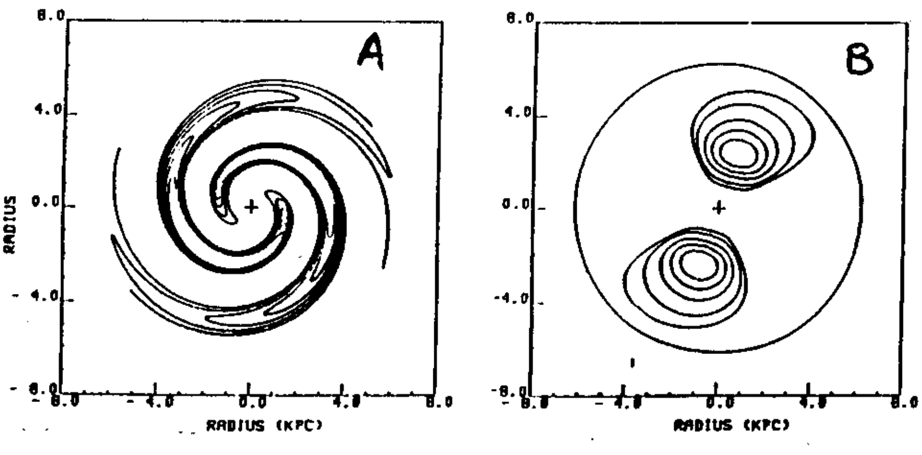


$\ln J$

$J \propto$ active disk density Σ_a

$J = \frac{\pi G \sigma}{r \kappa^2}$

$$\boxed{\frac{Q^2}{4} = \frac{1}{K} - \frac{(1-\nu^2)}{K^2 + \frac{J^2}{(1-\nu^2)}}}$$



Bertin IAU (100) 1982

TWO REGIMES (for the cubic in K)

(A) low-J limit (low disk mass) "large halo" * (three real roots for K)

$J \sim \varepsilon_0 \ll 1$ — low density

and

$\frac{r^2 k_r^2}{m^2} \gg 1$ — tightly wound spiral

$$\Rightarrow (\omega - m\Omega)^2 = \underbrace{c^2 k^2 - 2\pi G \sigma |k| + \kappa^2}_{\text{short + long waves}} + \overbrace{(\text{J-corrections})}^{\Delta}$$

$$\Rightarrow u'' + \frac{1}{\varepsilon_0^2 Q^2}\left[\nu^2 - 1 + \frac{1}{Q^2} + \Delta\right] u = 0$$

(B) high-J, open wave limit (high disk mass) "no or little halo" * (one real root for K)

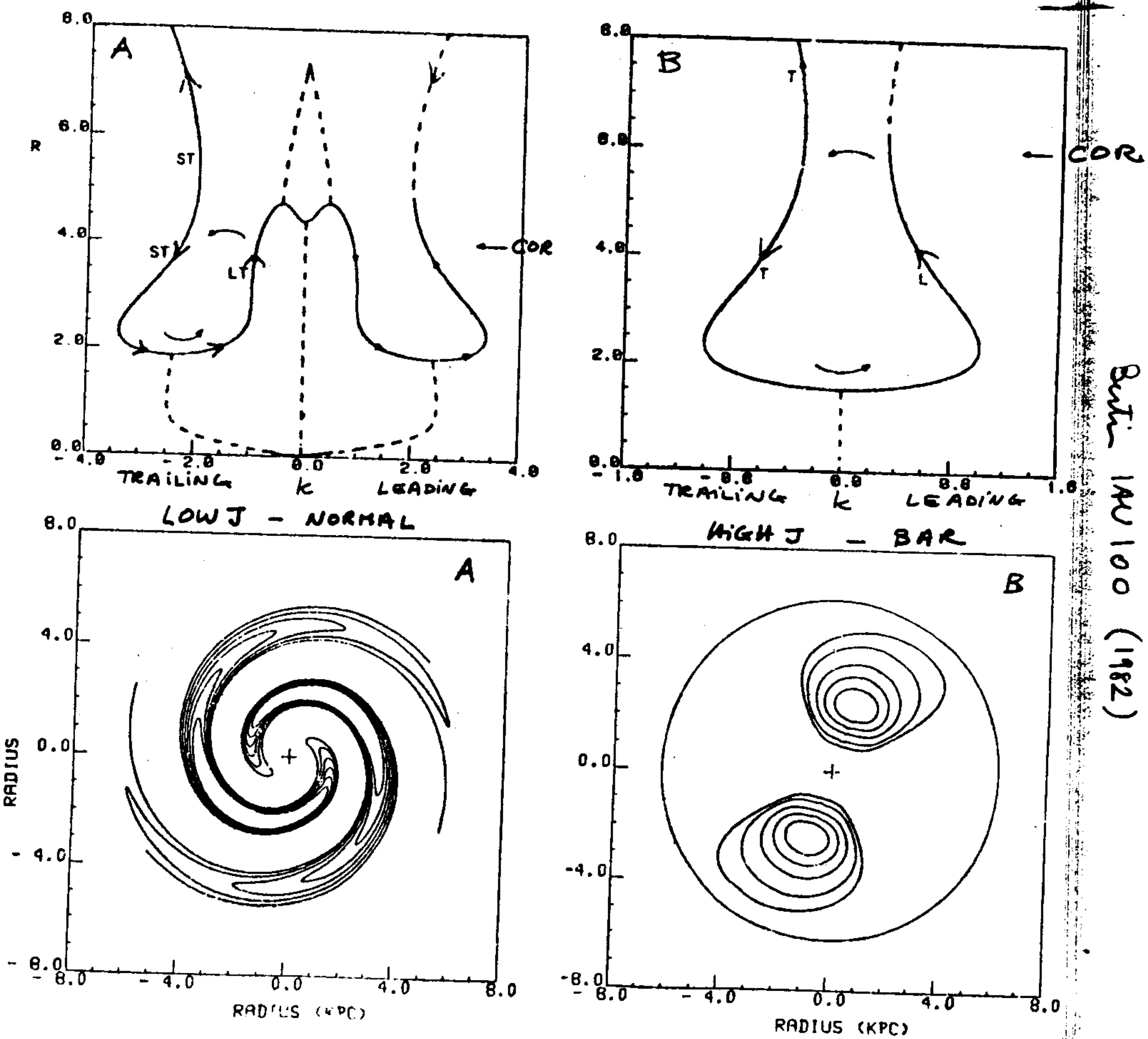
$J = O(1)$ — high density

$\frac{r^2 k_r^2}{m^2} < 1$ — open waves

$$Y'' + \underbrace{(\qquad)}_{\text{leading + trailing waves}} Y = 0$$

* but thickness can also count in making the effective/active disk mass low

Bertin IAU 100 (1982)

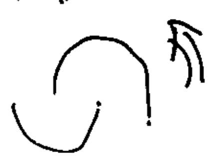


$c \leftarrow c_r$

c_g^2 / c_*^2

$\frac{1}{Q} \simeq \frac{1}{Q_*} + \frac{1}{Q_g}$

TRAILING



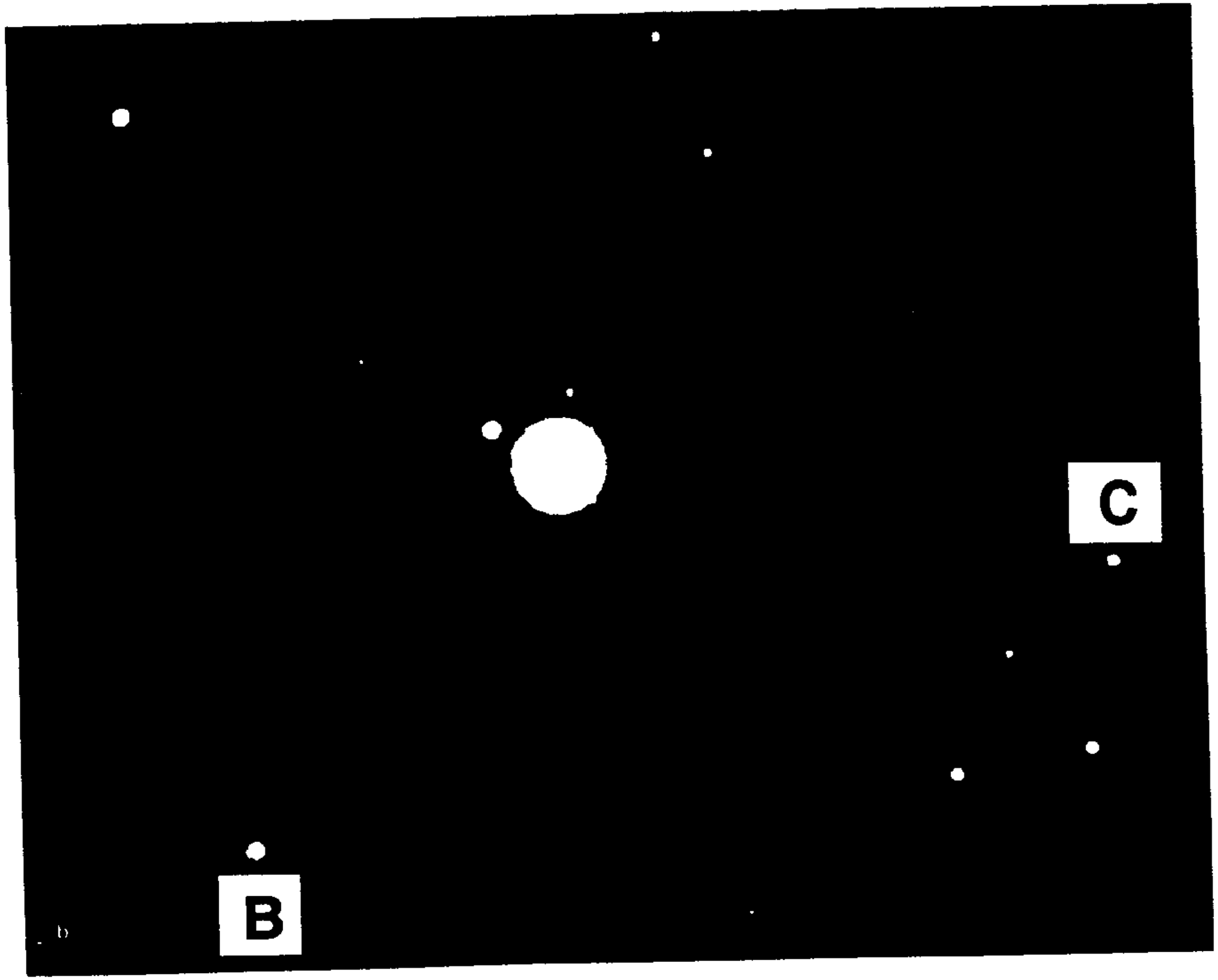
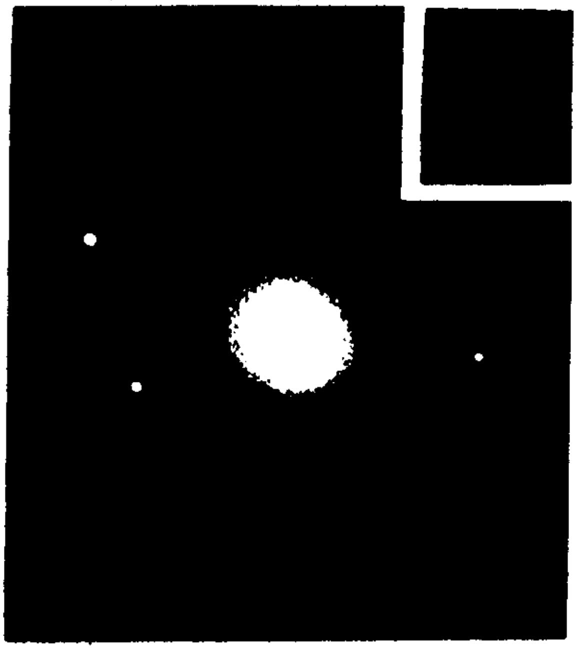


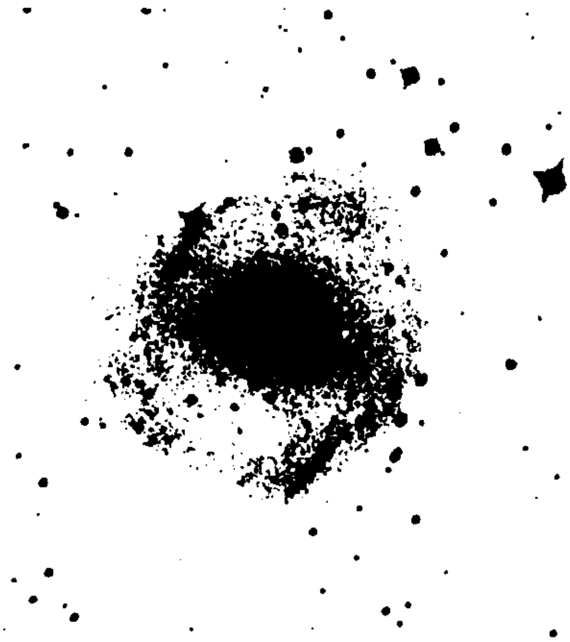
Fig. 6b. NGC 4622, observed at K' from Mauna Kea. The stellar density wave crests in NGC 4622 are remarkably thin, well defined, and long (traced for more than 360°). This is strongly indicative of small stellar epicycles and a cool, light Population II disk

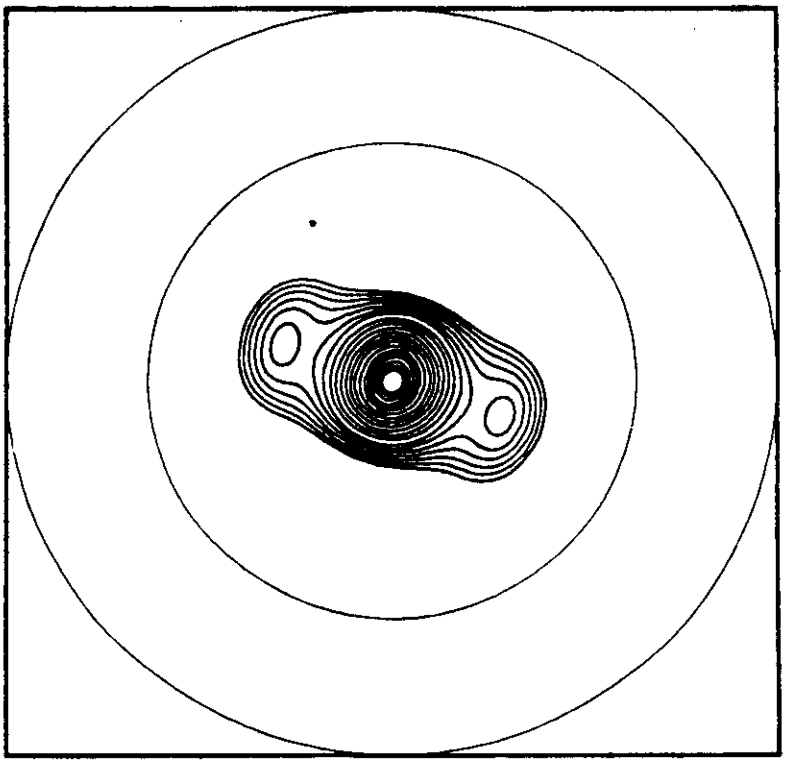
Block, Bertin, Stockton, Grosbøl, Moorwood, Peletier
AA 288 (1994) 365

N2859



N2217





BAR
MODE!

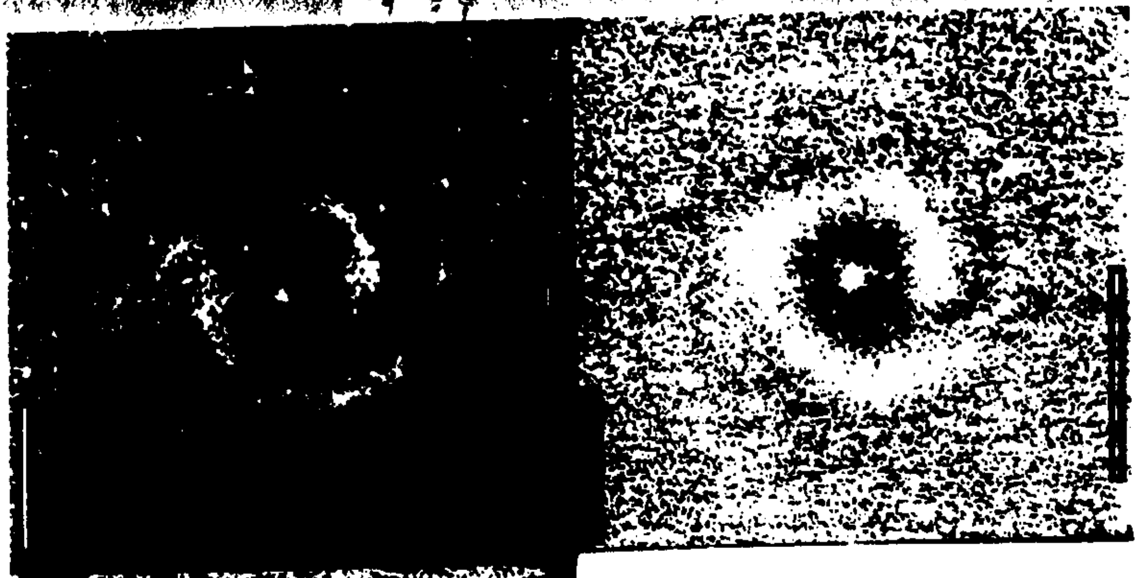
E3

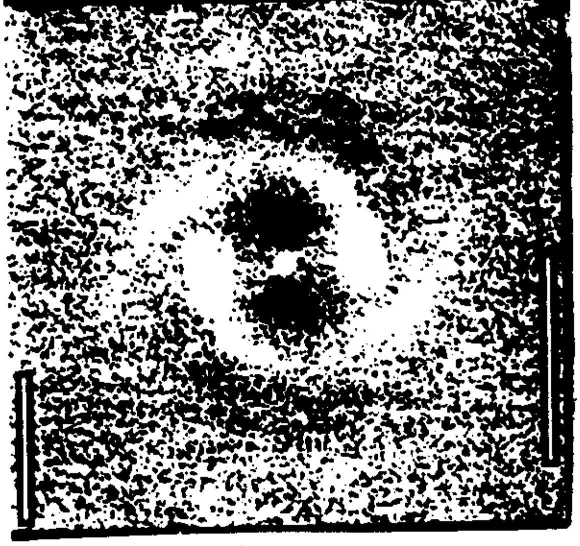
$\delta = -10\%$

$\Omega_{p} = 1.225$

$r_{a} = 2$

Slowe (1986)





BAR MODE!

BLLT, ApJ 338 (1989) 78
Bertin, Lin, Lowe, Thurstans

cf. D. Elmegreen 1996!!
Near-IR

For "interference patterns" in M81,
see Elmegreen in IAU 146 (1991) p. 113

FIG. 1.—(?) NGC 1300

For bars: see also Shaw, Combes, et al 1993
Combes & Elmegreen 1993

PERSISTENCE OF SPIRAL STRUCTURE IN GALAXIES

$\boxed{\text{"WINDING DILEMMA" FOR MATERIAL ARMS}}$

DENSITY WAVES

$\boxed{\text{GROUP PROPAGATION OF DENSITY WAVES}}$

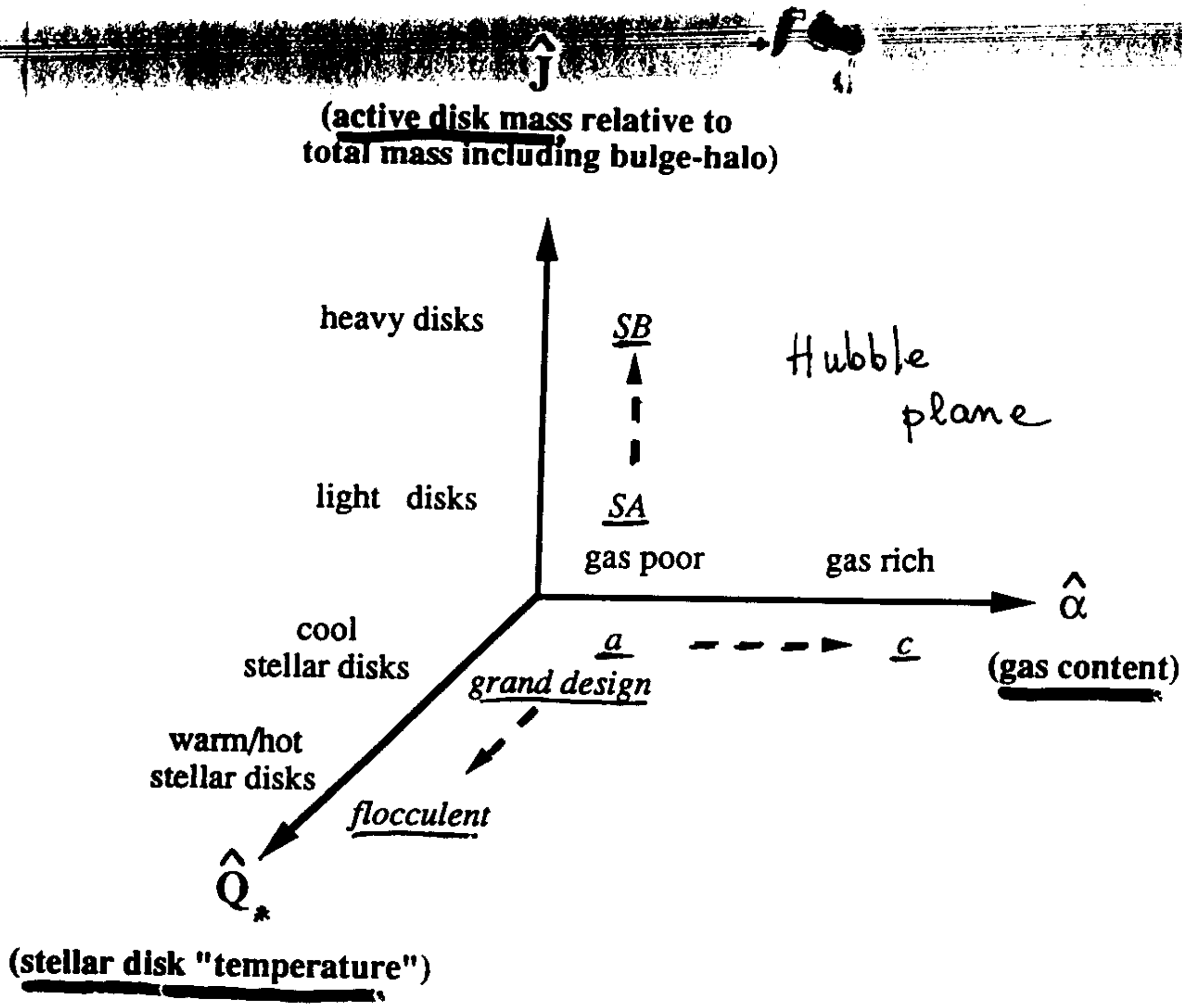
GLOBAL SPIRAL MODES
STANDING WAVES

$\boxed{\text{PERENNIAL HEATING OF STELLAR DISKS}}$

SELF-REGULATION

GAS !

dark matter



Bertin IAU 146
p. 102

	"Pop II" stars	"Pop I" gas
normal, grand design	active	active
normal, flocculent	inactive	active
barred	active	passive

$$\alpha = \frac{\sigma_g}{\sigma_*} \qquad \beta = \frac{c_g^2}{c_*^2}$$

A SIMPLE FAMILY OF BASIC STATES

$$V = V_\infty \frac{r}{r_\Omega}\left[1 + \left(\frac{r}{r_\Omega}\right)^2\right]^{-1/2}$$

$$\sigma = \sigma_{00}(1+\Delta)\, e^{-r/h} f + \sigma_g$$

$$Q = Q_{OD}\left[1 + q\, e^{-(r/r_Q)^2}\right] = \frac{c\kappa}{\pi G \sigma}$$

$$f = 1 - f_0(r/r_{cut}) + \frac{1}{6} f_0(r/r_{cut}) \exp(r/h)$$

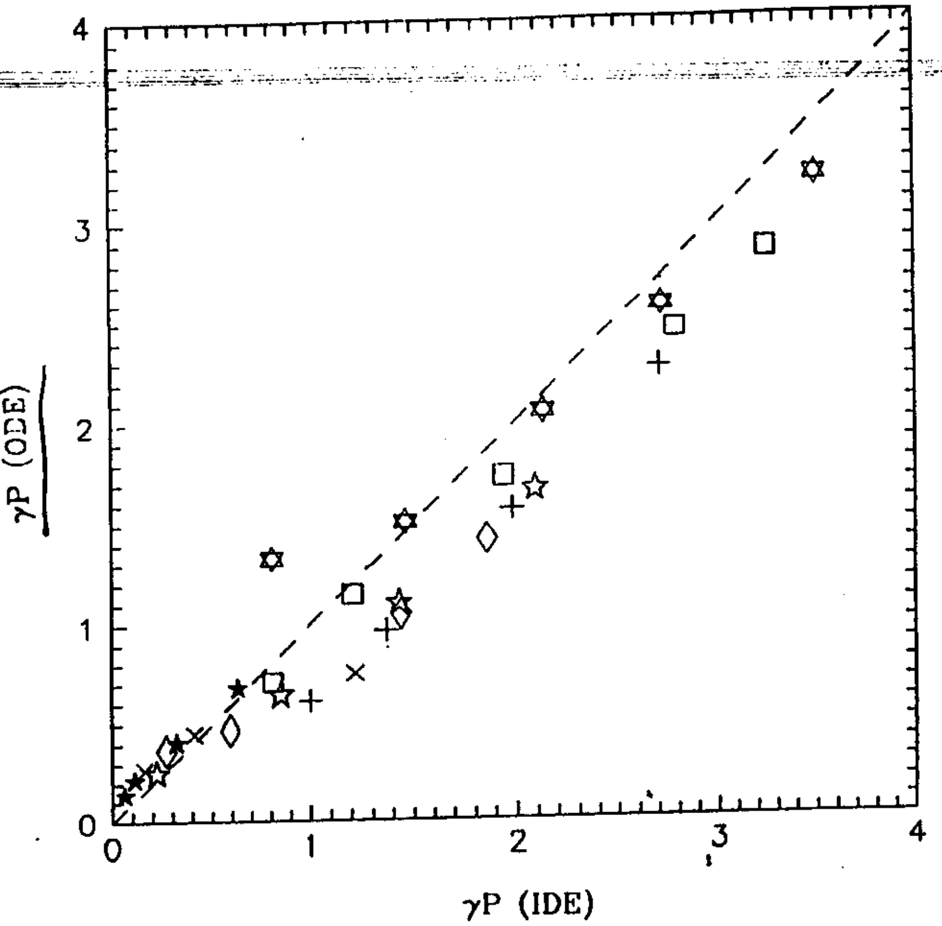
$f_0(x) = (1+4x)(1-x)^4$ for $x \leq 1$, $f_0 = 0$ for $x > 1$

three scalelengths : r_Ω, h, r_Q

magnitude parameters : V_∞, σ_{00} ; Δ, Q_{OD}, q

For $r_\Omega = 2$, $f = 1$, maximum disk : at $r = 4h$ disk to total mass ratio R_M is

$$R_M \approx 0.38(1+\Delta)$$



✡ : $r_Q = 2, Q_{OD} = 1$

☆ : $r_Q = 2, Q_{OD} = 1.2$

★ : $r_Q = 2, Q_{OD} = 1.4$

□ : $r_Q = 3, Q_{OD} = 1$

◇ : $r_Q = 3, Q_{OD} = 1.2$

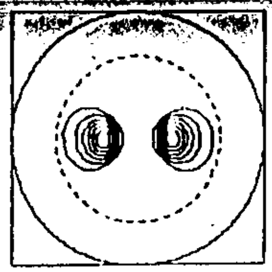
+ : $r_Q = 4, Q_{OD} = 1$

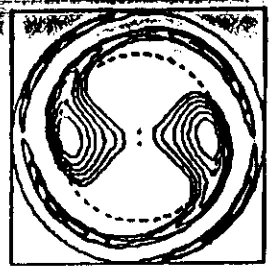
× : $r_Q = 4, Q_{OD} = 1.2$

$m = 2$

SBO SB(s)

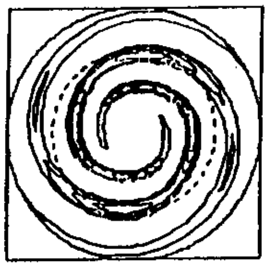
$\gamma P = 0.1$

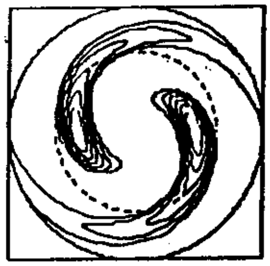




$\gamma P = 0.52$

$\gamma P = 0.6$





$\gamma P = \underline{3.00}$

(?)

S (low growth) S (high growth)

FOCUS ON BASIC STATES SUBJECT TO

MODERATELY UNSTABLE MODES ONLY !

SB0

Q_∞	=	1.500	r_{co}/h	=	2.27
Δ	=	15%	r_{olr}/h	=	3.96
r_Q	=	2.0	r_{ce}/h	=	0.57
r_{cut}	=	2.0			
r_Ω	=	2.0	J_{co}	=	0.604
			Q_{co}	=	1.500
Ω_P	=	15.0	s_{co}	=	0.954
γP	=	0.10			

SB(s)

Q_∞	=	1.000	r_{co}/h	=	2.49
Δ	=	15%	r_{olr}/h	=	4.31
r_Q	=	6.0	r_{ce}/h	=	0.30
r_{cut}	=	6.0			
r_Ω	=	2.0	J_{co}	=	0.538
			Q_{co}	=	1.096
Ω_P	=	13.8	s_{co}	=	0.961
γP	=	0.52			

S (low growth)

Q_∞	=	1.000	r_{co}/h	=	1.29
Δ	=	−35%	r_{olr}/h	=	2.27
r_Q	=	2.0	r_{ce}/h	=	0.69
r_{cut}	=	8.0			
r_Ω	=	1.5	J_{co}	=	0.492
			Q_{co}	=	1.002
Ω_P	=	26.1	s_{co}	=	0.922
γP	=	0.60			

S (high growth)

Q_∞	=	1.000	r_{co}/h	=	1.21
Δ	=	15%	r_{olr}/h	=	2.20
r_Q	=	2.0	r_{ce}/h	=	0.47
r_{cut}	=	2.0			
r_Ω	=	2.0	J_{co}	=	0.858
			Q_{co}	=	1.004
Ω_P	=	26.7	s_{co}	=	0.855
γP	=	3.00			

(?)

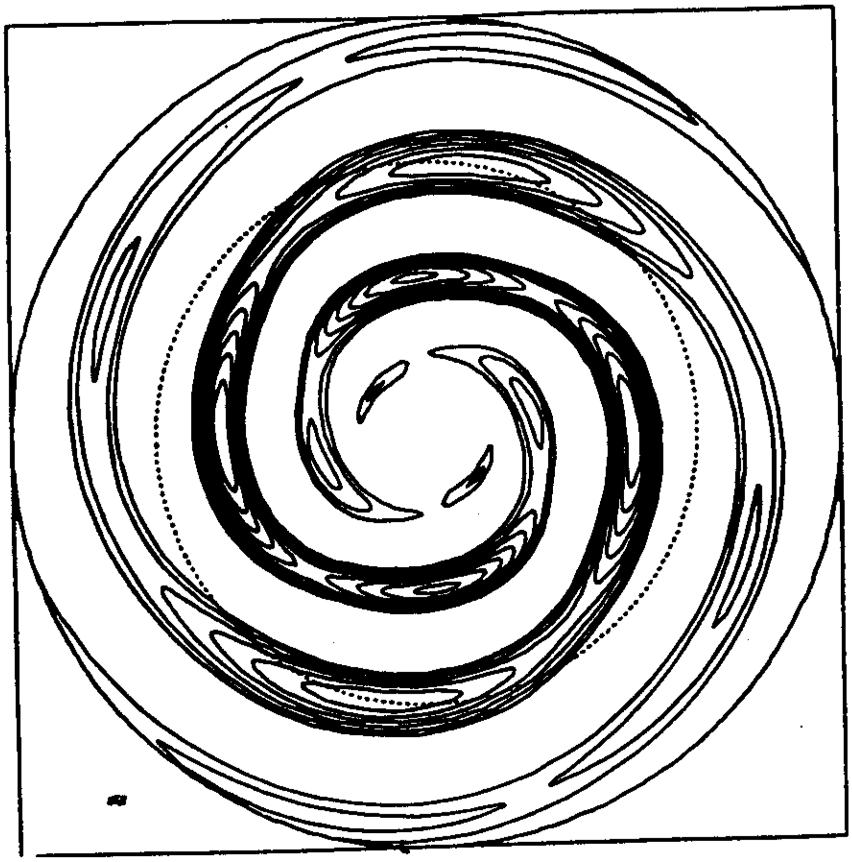
?

Bertin, Lin, Lowe & Thurstans Ap.J. 338 (1989)

I. 338, 78-103

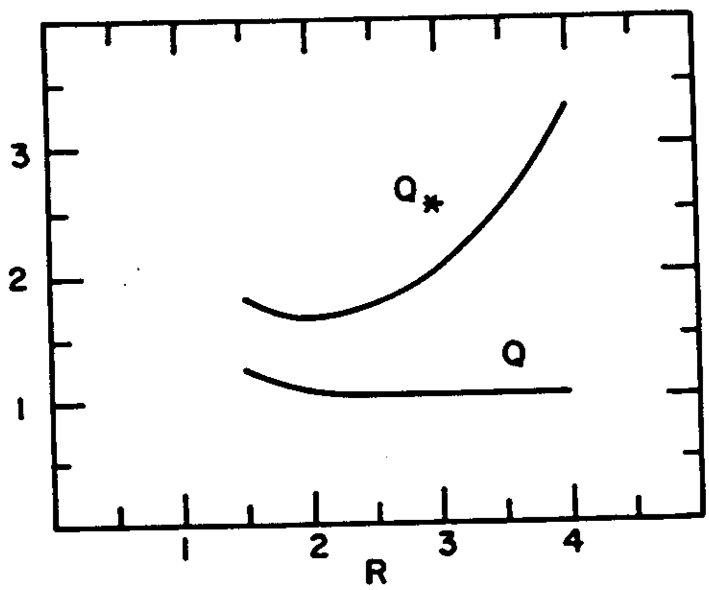
II. 338, 104-120

Bertin, Lin, Lowe, Thurstans   ApJ 338 (1989)



note modulation along the arms!

FIG. 8.—Multiwinding spiral mode. This particular mode is outside the main surveys presented in § II. The basic parameters are $Q_{OO} = 1$, $r_Q = h_*$, $\Delta = 7\%$, and $r_{co} = 6h_*$. This model, with a major change in density distribution, represents a case where the active disk essentially coincides with a thin Population I layer. The interesting properties of this mode are its multiple winding and its radial extent (the dotted circle is at $r_{co} \sim 2.9h_*$).



Q_* increasing outwards!

FIG. 9.—Behavior of the effective Q-profile and of the corresponding parameter Q_*, defined for the stellar component alone, for the model subject to the spiral mode displayed in Fig. 8. The stellar disk may appear to be very hot even when the disk is effectively cool.