DENSITY WAVES IN GALAXY DISKS CONTAINING GAS

G. BERTIN
Scuola Normale Superiore
Piazza dei Cavalieri
Pisa 56126-I
Italy

ABSTRACT. The cold interstellar medium plays a dominant role in determining the observed spiral structure in galaxies not only because it is the site of the generation of young and bright objects, but also because it is both a source of excitation (Jeans instability) and of regulation (since it can dissipate) for the overall dynamics of the disk. Here I review a physical picture of spiral galaxies developed in the last few years and present recent results on the mechanism of self-regulation of the disk, on the modeling of individual objects, and on the modeling of categories of spiral galaxies (morphological classification).

1. INTRODUCTION

The cold gas component, while recognized very soon to provide through shocks (Roberts and Shu 1972) a saturation mechanism for growing spiral modes at finite amplitudes, has been traditionally treated by dynamicists as a tracer of the spiral field generated in the stellar disk. Gas was also known to be a source of excitation (see Lin and Shu 1966), but in the overall picture it has usually been taken to be of secondary dynamical importance, given the fact that a large fraction of galaxy masses is non-gaseous. In contrast, in the physical picture that is now emerging (see Bertin et al 1989a and references therein), at least for normal (non-barred) spiral galaxies, gas plays a dominant, active, dynamical role, for the simple reason that, in the absence of dissipation, which can be supplied by the gas, stellar disks would continually heat and spiral structure, even if present initially, would rapidly die out. Therefore, recognizing the proper role of gas, as a "thermostat" that keeps the outer disk of spiral galaxies dynamically cool (see Sect. 2), resolves the third, most subtle kind of persistence problem for spiral structure. (The first persistence problem, known as the winding dilemma for material arms, is resolved by invoking the presence of density waves; the second persistence problem, posed by the propagation of wave packets (Toomre 1969), is resolved by the concept of global spiral modes.)

A second point to be emphasized is that data provide just a partial, blurred view of the structure of galaxies. Not only are key structural parameters, such as disk mass, still uncertain by a factor of two, but other

F. Combes and F. Casoli (eds.), Dynamics of Galaxies and Their Molecular Cloud Distributions, 93–104.

quantities, such as the radial velocity dispersion profile in the stellar disk of external galaxies, are likely to be well beyond the reach of direct measurements. The situation is complicated further by the fact that dynamical studies indicate that simple models show a collective behaviour that is very sensitive to various parameters, such as Q, which are, strictly speaking, not directly observed even if "perfect" data were available (see Sect. 3). Actually our goal is to take advantage of such sensitivity of collective dynamics and to bring the structure of galaxies in sharper focus by looking through the dynamical window (Bertin 1990a). This point of view leads to a general physical framework for categorizing all types of spiral galaxies (see Sect. 4).

"WINDING DILEMMA" for MATERIAL ARMS	DENSITY WAVES
GROUP PROPAGATION of DENSITY WAVES	GLOBAL SPIRAL MODES
PERENNIAL HEATING of STELLAR DISKS	SELF-REGULATION

Table 1. Three persistence problems for spiral structure

1.1 Some observed gas properties

The most direct information on the cold gas component in spiral galaxies derives from HI studies (e.g., see Bosma 1978, Wevers 1984, Warmels 1986, Begeman 1987) which show that it is generally much more extended than the stellar disk. Measuring other forms of cold gas is not so easy; it appears that the inner disk should be more clumpy and contain sizable amounts of molecules (e.g., see Young and Knezek 1989), while the outer gas disk is probably smoother and made mostly of atomic hydrogen (and cosmological helium). At intermediate and large radii ($r>2h_*$; here h_* denotes the exponential scalelength of the optical disk) the *local* gas to star surface density ratio $\alpha=\sigma_g/\sigma_*$ can be easily larger than 15%. The gas layer is fairly thin ($z_g<z_*$), but flares out and may be warped in the outer regions where the local gravity gets smaller (see van Woerden 1979). Random motions in the cold gas component appear to be in the range $c_g \approx 4$-8 km/s without sizable variations from galaxy to galaxy (see Dickey et al 1990). A number of gas disks display a very smooth kinematical structure indicating a high degree of symmetry in the underlying gravitational field. On the other hand, some spiral galaxies are observed with less regular HI distributions and kinematics which are suggestive of episodic gas accretion (Sancisi 1990).

1.2 Small scale physical processes

Since the velocity dispersion in the cold gas is so low, the natural scale associated with it is very small, of a few hundred parsecs. Many interesting studies of the gas have thus focused on the "small" scale, from the substructure of spiral arms (e.g., see Balbus & Cowie 1985, Elmegreen 1987, Balbus 1988) down to the issues related to the detailed dynamics of molecular clouds (see Myers 1987, McKee 1989, Elmegreen 1990) and to the problem of star formation (see Shu et al 1987, Tenorio-Tagle & Bodenheimer 1988). Of course, star formation is then connected back to the appearance of large scale spiral structure (see Roberts 1969, Seiden 1983, Elmegreen 1985, Allen et al 1986, Vogel et al 1988, Cepa and Beckman 1990, Rand and Kulkarni 1990), although it should be admitted that star formation can proceed via different mechanisms some of which independent of waves and spiral structure. In this paper I will not discuss these important points, but rather I will concentrate on the role of gas in determining the overall stability of the disk and on its impact on the dynamics of large scale spiral structure.

1.3 Active gas

Referring to the large scale structure of spiral galaxies, distinction can be made between the case of passive gas and that of active gas (Bertin and Lin 1987). When a bar is well developed, gas is thought to be mostly passive, so that the large scale spiral structure in the gaseous component of many barred galaxies should be seen as driven by the stellar bar (see Sanders & Huntley 1976). In general, since the response in the cold gas component can be very high, one can ask what is the expected relative share of the gas and of the star component in the resulting spiral field. Issues of this kind have been tackled either via analytical techniques (Lubow et al 1986) or via numerical simulations (see Roberts and Adler 1988). In the following, on the basis not only of the classical concepts of Jeans instability, but especially of the description of a mechanism of self-regulation, it will be argued that for *normal* spiral galaxies cold gas plays a dominant active role on the overall spiral structure.

The dynamical effects of the presence of a colder component in galaxy disks have often been investigated in terms of numerical experiments (Miller et al 1970, Quirk 1971, Sellwood & Carlberg 1984, Carlberg & Freedman 1985). Especially now that very powerful instruments to carry out two-component experiments (Hernquist 1989) have become available, great attention should be paid to an accurate modeling of the intervening physical processes in order to gain a realistic simulation of the dynamics of such complex systems.

1.4 Dynamical mechanisms

The linear theory of dynamical mechanisms that govern density waves in self-gravitating disks is probably all under control. A basic amplification mechanism (overreflection at corotation of waves that carry energy from a region of negative energy density, $r<r_{co}$, to a region of positive energy density, $r>r_{co}$) and various possible channels of wave propagation and refraction, with feedback from the inner parts of the galaxy, are the main ingredients required to describe the large scale dynamics of waves and modes

https://doi.org/10.1017/S0074180900243659 Published online by Cambridge University Press

(see Bertin et al 1989b and references therein). In contrast, the non-linear theory is probably all to be discovered. Much of the difficulty in developing such a non-linear theory resides in the problem of modeling a true global two-component system.

1.5 Long-term evolution

Beyond the saturation of a given spiral mode (Roberts and Shu 1972, Shu 1985, Lubow 1986), a mechanism of self-regulation can actually be justified whereby the overall instability level of the disk, and therefore the key dynamical parameters of the basic state, are regulated by the gas as a result of its capability to dissipate (see next Section). On the other hand, gas is continually transformed into stars, and one could wonder how long the gas layer can survive given the current rates of star formation (Larson, Tinsley, and Caldwell 1980). "Measuring" star formation rates is a difficult subject (Kennicutt 1983). It is plausible that episodic gas accretion may help revive occasionally the dynamics of the disk, but current data probably do not require a continual gas infall into the disks of normal galaxies, as sometimes argued (Quirk & Tinsley 1973, Gunn 1981). It seems that our limited knowledge of various physical processes and of key structural parameters of galaxies makes it premature to draw firm conclusions on the long term evolution of galaxy disks.

2. SELF-REGULATION

The term self-regulation is used in a variety of contexts to indicate the presence of competing mechanisms, usually characterized by multiple time scales, that manage to bring and to keep a system in a quasi-steady state. Thus, a system under self-regulation is expected to evolve slowly and to be associated with a fairly small region of the available parameter space of interest. As an example outside the astrophysical context, we may refer to the case of the chemical reactions that participate in the combustion of flames. In the following (see Sect 2.3) I shall describe a simple picture for the self-regulation of galaxy disks where the stellar and the gas components are dynamically coupled. These appear to be the systems where grand design spiral structure can develop.

2.1 Regulation processes in the absence of gas

A purely stellar disk with finite thickness would be subject to a perennial transformation of ordered kinetic energy into random motions as a result of collective instabilities and possibly of the scattering of orbits by "external" driving forces. Thus it seems that a purely stellar disk, once hot and stable enough, cannot return back to a cooler state. In this sense self-regulation in such a system cannot take place.

Two possibilities have been explored in order to see whether the evolution of an initially unstable stellar disk can be slowed down. As a mechanism for the saturation of a single global mode, it has been suggested (Contopoulos & Grosbol 1986) that the amplitude of spiral modes is limited by the nature of non-linear orbits; such a process seems to operate quite efficiently outside the 4:1 resonance. On this basis, one might hope that even in smooth armed galaxies (Strom & Strom 1978, Sandage 1983) spiral structure is long-lasting. Another point to be considered is that, since heating processes are rapidly turned off as the random motions of the stars increase, the disk is bound to be subject to only a very slow evolution once it reaches a state of moderate instability. This argument, although generally true, should be better quantified. In conclusion, spiral structure in purely stellar disks, even if initially present, does not appear to be sufficiently robust, because heating of stellar disks is probably inevitable.

2.2 Regulation processes in the interstellar medium

The interstellar medium is a much more complex system and various processes of regulation have been studied for it. However, these investigations generally address the physics of the interstellar medium as essentially "isolated" from the dynamics of the stellar disk. Therefore, very often these studies consider the smallest scale phenomena (Myers 1987, McKee 1989). Concepts of self-regulation are well explored (Franco & Cox 1983, Tenorio-Tagle & Bodenheimer 1988). Starting with the work of Spitzer (1968, 1978), particulary interesting are the studies aimed at explaining, or determining, through the concept of self-regulation, the density and the temperature in the hot medium (McKee & Ostriker 1977), the mass spectrum of interstellar clouds (Cowie and McKee 1977, Kwan 1979, Cowie 1980), and especially the velocity dispersion of giant molecular clouds (Jog & Ostriker 1988). In a sense, even the recent suggestions on star formation processes by Kennicutt (1989; see also Quirk 1972) appear to focus on regulation processes within the dynamics of the interstellar medium.

2.3 Self-regulation of a coupled disk of stars and gas

A galaxy disk can be kept dynamically cool, even if the stellar component continually heats, through a process of self-regulation that couples the dynamics of the stars to that of the gas. That such a mechanism is required in supporting spiral structure in non-barred galaxies has been recognized quite recently (Bertin & Lin 1987, Bertin & Romeo 1988, Bertin et al 1989a). In contrast to earlier papers where similar ideas had been expressed in general terms (see especially Miller, Prendergast, and Quirk 1970; Sellwood & Carlberg 1984 and Ostriker 1985), the more recent studies show in a quantitative way why and for which morphological types the gas is needed and how the current data on the gas distribution in galaxies support the picture that the outer disk of non-barred spirals may indeed be kept cool by the process of self-regulation and is thus the site where large scale spiral structure is excited and maintained. In specific terms, these investigations relate the process of self-regulation to the expected relevant Q-profile in galaxy disks (Bertin et al 1989a). Indeed, it is from these quantitative investigations that a unified framework may be drawn for interpreting the observed morphologies of spiral galaxies (see following Sect. 4).

Here I will illustrate the main features characterizing the self-regulation of a coupled disk of stars and gas by showing some results of a numerical integration of a simplified mathematical model introduced by Bertin & Romeo (1988; eqs (20), (21), and (24)). This model is zero-dimensional, i.e. it describes an evolution problem where the various parameters are taken to be representative of a typical region of the galaxy, such as the outer disk ($r \approx 3h_*$).

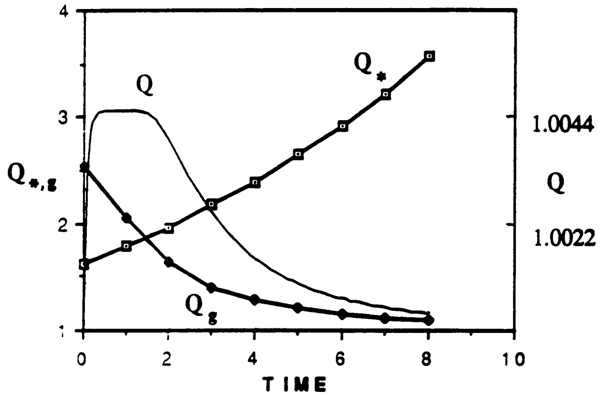

Figure 1. Demonstration of the mechanism of self-regulation

The case shown in Fig. 1 was computed only for demonstration purposes and refers to a gas to star density ratio α=0.45. In this extremely simple example the cooling term in the gas component (g) is taken to be constant and the two heating terms (f-terms) that couple the evolution of each component, i.e. of $Q_* = c_* \kappa/\pi G \sigma_*$ and $Q_g = c_g \kappa/\pi G \sigma_g$, to the collective dynamics through the (effective) Q-parameter are assumed to be proportional to $Q^{-\mu}$, where μ is a constant (different values of μ are introduced for gas and for stars). The definition of Q as a function of Q_* and Q_g (Bertin and Romeo 1988, eq. (16)) follows from an analysis which is the limit of zero-thickness of that to be described in the next section (Sect.3). The evolution of the system is characterized by a general cooling of the gas component (Q_g decreases) and by a general heating of the stellar component (Q_* increases), accompanied with a *very efficient thermostat for the level of dynamical stability of the combined system* ($Q \approx 1$). Of course, the reason for this self-regulation resides in the sensitivity of the heating terms to Q. On the other hand, a condition of marginal stability with respect to local Jeans collapse allows for moderate instability of large scale spiral modes (via overreflection; see Bertin et al 1989a,b).

Work is now in progress (Bertin and Ostriker 1990) aimed at giving a more realistic physical description of self-regulation, by incorporating, among other effects, the role of star formation and a more detailed picture of the various cooling and relaxation processes.

3. MODELING INDIVIDUAL GALAXIES

Galaxies are very complex systems that include many stellar and gaseous components. In order to study their dynamics a sensible procedure is to start out by adopting the simplest possible model, e.g. that of an "active" one-component self-gravitating fluid disk of zero thickness embedded in a background rigid (i.e. inactive) field which is primarily associated with the bulge-halo mass distribution. The disk equilibrium configuration is defined in terms of three functions, i.e. the rotation curve V(r), which incorporates the effects of the background field, the disk density profile $\sigma(r)$ and the equivalent acoustic speed profile c(r). Then, the dynamical studies show why and how such a simple model breaks down and should be improved. In particular, the role of gas and the three-dimensional distribution of matter must be incorporated, at least by guiding our choice of the profiles $\sigma(r)$ and c(r) (see Bertin et al. 1989a). For many purposes, even if in principle it would be desirable to move on to a more realistic and complex model (see Bertin 1990b), we may still have to refer to the original simplified model just because certain technical tools, such as a numerical code for the study of the linear global stability problem, may not be available for the more complex case.

Therefore, a crucial issue to be addressed is the modeling procedure. On the one hand, as it would be natural if we had a "perfect" knowledge of the structural parameters of a galaxy, we would like to devise a unique prescription to set the most appropriate profiles $\sigma(r)$ and c(r) on the basis of the observations. On the other hand, since we have only an "imperfect" knowledge of those parameters (see previous Sect. 1), we would also like to consider the *inverse* problem. In fact, dynamical constraints may narrow down the range of options for $\sigma(r)$ and c(r) as specified by observations alone and we would like to go back and see what are the implications of these dynamical constraints on the structural parameters of the physical system under investigation. (To this step I referred earlier as "looking through the dynamical window".) This latter process obviously does not lead to a unique answer. Such ambiguity is somewhat similar to that known in the theory of pattern recognition where a combination of simple geometrical elements are used by the machine to "reconstruct the real picture".

In the following, I will outline a general procedure to tackle the modeling problem in the context of the study of the linear modal analysis of the global stability of galaxy disks. To my knowledge a corresponding procedure is not yet available for non-linear and/or time-dependent analyses.

3.1 Modeling two-component disks

In order to focus on some essential features of the general problem, we refer to an idealized situation where the system to be modeled is far simpler than the real galaxy to be studied but contains a number of properties that make it far more realistic than the one-component system studied by the numerical codes at our disposal. Let 1(ZT) (one component zero thickness) be the model specified by V(r), $\sigma(r)$, and c(r). Let 2(FT) be the system that we want to model, made of two components, that we call stars and gas but we treat both as fluids, with finite thickness in the same force field; then 2(FT) is specified by V(r), $\sigma_*(r)$, $c_*(r)$, $z_*(r)$, $\sigma_g(r)$, $c_g(r)$, $z_g(r)$. The thicknesses are defined in such a way that the projected column densities are related to the peak (equatorial) densities by $\sigma_*=2\bar{\rho}_* z_*$ and $\sigma_g=2\bar{\rho}_g z_g$. If each component is vertically isothermal, the volume density vertical profiles differ from the sech^2-solution typical of the one component isothermal slab; still, a useful relation involving the vertical dispersion speeds can be identified:

$$(1+\alpha)^2 = \frac{c_{z*}^2}{\pi G \sigma_* z_*} + \frac{c_{zg}^2}{\pi G \sigma_g z_g}\alpha^2 \tag{1}$$

https://doi.org/10.1017/S0074180900243659 Published online by Cambridge University Press

Clearly this system 2(FT) has degrees of freedom that 1(ZT) does not possess. On the other hand, we feel that, in certain regions of the relevant parameter space and for certain purposes, we should have an adequate description of the dynamics of 2(FT) by a study of 1(ZT) if we properly choose the two profiles $\sigma(r)$ and $c(r)$.

The procedure that we propose is based on the results of a *local* stability analysis. For 1(ZT), in the limit of tightly wound disturbances, the linear dispersion relation reads:

$$Q^2 = 4\,[\,\bar{\lambda} + (\nu^2 - 1)\,\bar{\lambda}^2] \tag{2}$$

where $\nu = (\omega - m\Omega)/\kappa$ is the dimensionless Doppler-shifted frequency, $Q = c\kappa/\pi G\sigma$, and $\bar{\lambda} = \kappa^2/2\pi G\sigma|k|$ is the dimensionless radial wavelength. The marginal stability curve in the $(\bar{\lambda}, Q^2)$ diagram is a parabola with maximum occurring at $\bar{\lambda}_{max} = 1/2$ and $Q_{max} = 1$. As is well known, the modal theory of normal spiral structure is based on waves that are described by (2) in the vicinity of $\bar{\lambda}_{max}$ and Q_{max} (see Bertin et al 1989b).

Consider now the local stability of 2(FT). The relevant dispersion relation, which can be derived following the procedure outlined by Bertin & Romeo (1988) and incorporating the effects of finite thickness as suggested by Vandervoort (1970), is of the form:

$$Q_*^2 = \mathcal{D}(\hat{\lambda}, \nu^2; \alpha, \beta, \hat{z}_*, \hat{z}_g) \tag{3}$$

where $\hat{\lambda} = \kappa^2/2\pi G\sigma_*|k|$, $\alpha = \sigma_g/\sigma_*$, $\beta = c^2{}_g/c^2{}_*$, $\hat{z}_* = z_*\kappa^2/2\pi G\sigma_*$, $\hat{z}_g = (z_g/z_*)\,\hat{z}_*$. In a $(\hat{\lambda}, Q_*^2)$ diagram we can plot the marginal stability curve as a function of the four parameters $\alpha, \beta, \hat{z}_*, \hat{z}_g$. Suppose that such a curve has its maximum at $\hat{\lambda}_{max}(\alpha, \beta, \hat{z}_*, \hat{z}_g)$ and $Q_{*max}(\alpha, \beta, \hat{z}_*, \hat{z}_g)$.

Here we argue that 1(ZT) is a good model of 2(FT) if the dispersion relations in the vicinity of their peaks are approximately mapped into each other. This is obtained by the following rescaling:

$$\hat{\lambda}/\hat{\lambda}_{max}(\alpha, \beta, \hat{z}_*, \hat{z}_g) = 2\bar{\lambda} \tag{4}$$

$$Q_*/Q_{*max}(\alpha, \beta, \hat{z}_*, \hat{z}_g) = Q \tag{5}$$

From the "data" $(\sigma_*, c_*, \alpha, \beta, \hat{z}_*, \hat{z}_g)$, these relations define the properties of the "equivalent" model (σ, c).

These prescriptions generalize the procedure formulated by Bertin & Romeo (1988) for the case $z_g = z_* = 0$ (2(ZT)). A way to check at a global level that 1(ZT), as determined by Eqs. (4) and (5), is a good model of 2(FT), is to compare the propagation diagrams for the relevant modes in the two systems, i.e. to plot $k=k(r)$ on the basis of (2) and of (3) for selected choices of the corotation radii. [A rescaling argument explains why the mapping of $2(FT) \rightarrow 1(ZT)$ is expected to be only approximately feasible in a ν-independent way. In order to incorporate this ν-dependence we should slightly reduce (by

https://doi.org/10.1017/S0074180900243659 Published online by Cambridge University Press

a factor $(1-v^2)$) the thickness of the disks in the inner regions of the galaxy.] Therefore, the mapping should be improved at the global level by minimizing the differences between the propagation diagrams for the relevant ranges of corotation radii.

3.2 Modeling external galaxies with normal spiral structure

We can describe the process of modeling individual galaxies in terms of an iteration procedure. When focusing on a given galaxy, the available data on the basic properties of the object under investigation would lead, following a procedure of the kind outlined in Sect. 3.1, to a reference model $1(ZT)_0$; given our imperfect knowledge of structural parameters, a whole range of 1(ZT) models around $1(ZT)_0$ would be compatible with the observations. At this stage one can perform a modal analysis of these 1(ZT) models in order to identify the most plausible $1(ZT)_1$ model (within the allowed range, but generally different from $1(ZT)_0$) in order to match the properties of the observed spiral structure for the galaxy under investigation. In particular, the following factors should be considered: (i) The extent of spiral structure, (ii) The pitch angle of spiral structure, (iii) The structure of spiral arms, (iv) The overall regularity of spiral structure. Then one should study the inverse problem in order to identify the available range of 2(FT) models compatible with $1(ZT)_1$. The iteration process would continue, because we should make sure that the identified 2(FT) model would not suffer from other undesired modes (such as open bar modes). Guidance to the iteration process would also be provided by self-regulation arguments of the kind described in Sect 2.

For the galaxy M81, as a significant step beyond the work of Visser (1977), efforts are under way, aimed at incorporating the most recent detailed data on spiral structure (Elmegreen et al 1989, Kaufman et al 1989a,b), that are now leading to a new dynamical model (Lowe, Lin, and Roberts 1990). In this work, starting from the class of 1(ZT) models discussed by Bertin et al (1990a), a 1(ZT) model has been identified that supports a mode that matches the observed spiral structure. A 2(FT) model has then been calculated, independently of the arguments given in Sect. 3.1 above, by imposing the wavenumber $k=k(r)$ suggested by the observed spiral pattern of M81 on the local stellar-fluid dispersion relation of Shu (1971). On the basis of such a dynamical model the response of the self-gravitating interstellar medium can be calculated. One feature of this new model is that it has a lighter disk with respect to the maximum disk solution (as defined, e.g., by van Albada & Sancisi 1986).

3.3 Modeling the Milky Way

The case of the Milky Way requires special treatment. For our galaxy in the vicinity of the Sun we have excellent detailed data on gas and stars, even though the amount of matter associated with the disk is still under debate (Bahcall 1984; Kuijken and Gilmore 1989). The rotation curve is reasonably well determined only inside the solar circle. Other profiles, such as $c_*(r)$(Lewis and Freeman 1989) have been measured, but with fairly large error bars. Being inside the disk, we do not have a clear picture of the overall spiral structure.

Therefore, we may aim at three different goals: (i) The determination of

https://doi.org/10.1017/S0074180900243659 Published online by Cambridge University Press

the local stability level with respect to tightly wound disturbances, (ii) A dynamical evaluation of the nature of spiral structure in our galaxy, (iii) A test of the implications of mechanisms of self-regulation on the radial profiles of some structural parameters of the disk.

The second point (ii), especially if the lighter disk of Kuijken & Gilmore (1989) is preferred, is likely to lead to the conclusion that spiral structure in the Milky Way is mostly gas supported and, possibly because of that, not so regular. As to point (iii), if the gas is really decoupled from the stars, we would expect self-regulation to constrain the radial profiles of the properties of the gas but to be less relevant for the properties of the stellar disk.

4 MODELING CATEGORIES OF GALAXIES

The modal approach to the morphology of spiral galaxies (see Bertin et al 1989a), together with the physical arguments described in the previous Sects. 2 and 3, naturally leads to a unified framework for modeling and interpreting all categories of spiral galaxies as currently observed. Here I attempt to summarize such a framework in its most simple (and probably oversimplified) form. According to such a picture, the various morphological types are put in correspondence with three key parameters: disk to bulge-halo mass ratio, gas content, and "temperature" of the stellar disk.

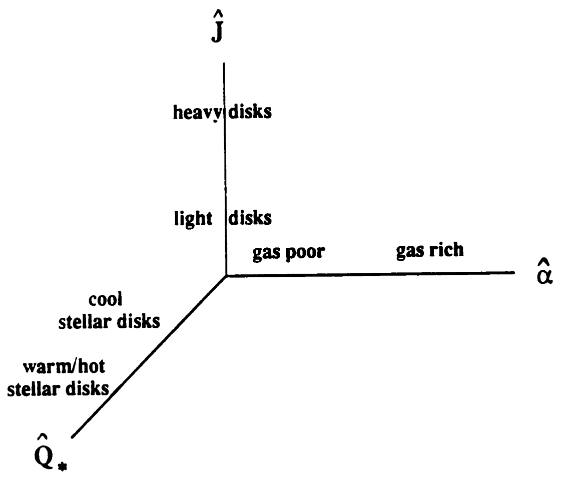

Figure 2. Schematic representation of the parameter space for modeling categories of spiral galaxies

Barred galaxies are expected to be associated with heavy disks. Their stellar disks should be quite warm, since in cooler disks rapid heating would take place. For these galaxies, the gas component would be mostly passive with respect to the large scale open bar driving, dominated by the stellar component; of course, gas would be active in determining small scale spiral structure. SB0 galaxies would be associated with warm, heavy, gas deficient disks.

Lighter disks would give rise to normal spiral structure. Grand design spiral structure would be generally associated with relatively cool stellar disks, for which the dynamics of stars can be well coupled with the dynamics of gas and consequently be self-regulated. Cool stellar disks with large amounts of gas should lead to multiple-armed spiral structure since the overall dynamics would tend to become gas dominated; for these objects, that are likely to appear less regular because too much excitation is available, tidal interaction may organize temporary coherent structure. On the other extreme, gas deficient, cool disks, that might originate smooth armed spiral structure, are likely to be transient.

Light disks with a warm or hot stellar component are bound to be characterized by a decoupled dynamics, where gas develops small scale spiral structure and stars are mostly unresponsive and "inactive". These systems would therefore appear to be flocculent. Gas deficient, warm, light disks would be classified S0.

The majority of galaxies is expected to have settled in a quasi-steady state where spiral morphology is evolving slowly. Special events, such as episodic gas accretion, may induce somewhat rapid changes in the spiral appearance, but then the system should quickly settle into a new quasi-steady configuration. Paradoxically, mergers and severe tidal interactions, to the extent that they may induce significant heating and thickening of the stellar component, may actually be responsible, if frequent, for many flocculent galaxies.

Reasonable indications on the long term evolution of spiral galaxies might be obtained from deeper studies of the processes of self-regulation.

Helpful conversations with C.C. Lin and J. Ostriker are gratefully acknowledged. This work is partially supported by CNR and MURST of Italy.

Allen, R.J., Atherton, P.D., Tilanus, R.P.J., 1986, Nature, **319**, 296
Bahcall, J., 1984, Ap. J., **276**, 169
Balbus, S.A. and Cowie, L.L., 1985, Ap. J., **297**, 61
Balbus, S.A., 1988, Ap. J., **324**, 60
Begeman, K., 1987, Ph.D. Thesis, Groningen
Bertin, G., 1990a, in "Windows on Galaxies", eds. G. Fabbiano et al, Kluwer, p.341
Bertin, G., 1990b, Ann. N.Y. Acad. Sci., **596**, 123
Bertin, G. and Lin, C.C., 1987, Pub. Astr. Inst. Czech. Acad. Sci., **69**(4), 255
Bertin, G. and Ostriker, J.P., 1990, in preparation
Bertin, G. and Romeo, A.B., 1988, Astr. Ap., **195**, 105
Bertin, G., Lin, C.C., Lowe, S.A., Thurstans, R.P., 1989a, Ap. J., **338**, 78
Bertin, G., Lin, C.C., Lowe, S.A., Thurstans, R.P., 1989b, Ap. J., **338**, 104
Bosma, A., 1978, Ph.D. Thesis, Groningen
Carlberg, R.G. and Freedman, W.L., 1985, Ap. J., **298**, 486
Cepa, J. and Beckman, J.E., 1990, Ap. J., **349**, 497
Contopoulos, G. and Grosbol, P., 1986, Astr. Ap., **155**, 11
Cowie, L.L., 1980, Ap. J. **236**, 868
Cowie, L.L. and McKee, C.F., 1977, Ap. J., **211**, 135
Dickey, J.M., Hanson, M.M., Helou, G., 1990, Ap. J., **352**, 522
Elmegreen, B.G. 1985, in "Star Formation", eds. R. Lucas et al, N. Holland, p.215
Elmegreen, B.G. 1987, Ap. J., **312**, 626
Elmegreen, B.G. 1990, in "The evolution of the interstellar medium", ed. L. Blitz, ASP Publishers, in press
Elmegreen, B.G., Elmegreen, D.M. and Seiden, P.E. 1989, Ap. J., **343**, 602

Franco, J., Cox, D.P., 1983, Ap. J., **273**, 243
Gunn, J.E., 1981, in "Astrophysical Cosmology", eds. M.S. Longair et al, Pont. Acad. Sci. p.233
Hernquist, L., 1989, Annals N.Y. Acad. Sci., **571**, 190
Jog, C.J. and Ostriker, J.P., 1988, Ap. J., **328**, 404
Kaufman, M., Bash, F.N., Hine, B., Rots, A.H., Elmegreen, D.M., and Hodge, P.W., 1989a, Ap. J., **345**, 674
Kaufman, M., Elmegreen, D.M., and Bash, F.N., 1989b, Ap. J., **345**, 697
Kennicutt, R.C., 1983, Ap. J., **272**, 54
Kennicutt, R.C., 1989, Ap. J., **344**, 685
Kuijken K.H. and Gilmore, G., 1989, M.N.R.A.S., **239**,605
Kwan, J., 1979, Ap. J., **229**, 567
Larson, R.B., Tinsley, B.M., and Caldwell, C.N., 1980, Ap. J., **237**, 692
Lewis, J. R. and Freeman, K.C., 1989, Astr. J., **97**, 139
Lin, C.C. and Shu, F.H. 1966, Proc. Natl. Acad. Sci. USA, **55**, 229
Lowe, S.A., Lin, C.C., and Roberts, W.W. 1990, in preparation
Lubow, S.H. 1986, Ap. J. Letters, **307**, L 39
Lubow, S.H., Balbus, S.A., Cowie, L.L. 1986, Ap. J., **309**, 496
McKee, C., 1989, Ap. J., **345**, 782
McKee, C.F. and Ostriker, J.P., 1977, Ap. J., **218**, 148
Miller, R.H., Prendergast, K.H., Quirk, W.J., 1970, Ap. J., **161**, 903
Myers, P.C., 1987, in "Interstellar Processes", eds. D.J. Hollenbach & H.A. Thronson, Reidel, p.71
Ostriker, J.P. 1985, in IAU Symp. 106, eds. H. van Woerden et al, Reidel, p.638
Quirk, W.J., 1971, Ap. J., **167**, 7
Quirk, W.J., 1972, Ap. J. Letters, **176**, L9
Quirk, W.J., and Tinsley, B.M., 1973, Ap. J., **179**, 69
Rand, R.J. and Kulkarni, S.R., 1990, Ap. J. Letters, **349**, L43
Roberts, W.W., 1969, Ap. J., **158**, 123
Roberts, W.W. and Shu, F.H., 1972, Ap. Letters, **12**, 49
Roberts, W.W. and Adler, D.S. 1988, Lecture Notes in Phys., **306**, 125
Sancisi, R., 1990, in "Windows on Galaxies", eds. G. Fabbiano et al, Kluwer, p.199
Sandage, A., 1983, in IAU Symp. 100, ed E. Athanassoula, Reidel, p.367
Sanders, R.H. & Huntley, J.M., 1976, Ap. J., **209**, 53
Seiden, P.E., 1983, Ap. J., **266**, 555
Sellwood, J.A. and Carlberg, R.G., 1984, Ap. J., **282**, 61
Shu, F.H. 1971 Astr. Gen. Rel., Vol. **2**, ed. M. Chrétien , Gordon & Breach, p.314
Shu, F.H. 1985 in IAU Symp. 106, ed. H. van Woerden et al, Reidel, p.530
Shu, F.H., Adams, F.C., Lizano, S., 1987, Ann. Rev. Astr. Ap., **25**, 23
Spitzer, L., 1968, "Diffuse Matter in Space", New York, Wiley
Spitzer, L., 1978, "Physical Processes in the Interstellar Medium", N. Y., Wiley
Strom, S.E. & Strom, K.M., 1978 in IAU Symp. 77, Reidel, p.69
Tenorio-Tagle, G. and Bodenheimer, P., 1988, Ann. Rev. Astr. Ap., **26**, 145
Toomre, A., 1969, Ap. J., **158**, 899
van Albada, T.S. and Sancisi, R. 1986, Phil. Trans. R. Soc. Lond. A, **320**, 447
Vandervoort, P.O. 1970, Ap. J., **161**, 87
van Woerden, H., 1979, in IAU Symp. 84, ed. W.B. Burton, Reidel, p.501
Visser, H.C.D. 1977, Ph. D. Thesis, Groningen
Vogel, S.N., Kulkarni, S.R., Scoville, N.Z., 1988, Nature, **334**, 402
Warmels, R.H., 1986, Ph.D. Thesis, Groningen
Wevers, B.M.H.R., 1984, Ph. D. Thesis, Groningen
Young, J.S. and Knezek, P.M., 1989, Ap. J. Letters, **347**, L55