SPIRAL TYPES

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ABSTRACT. Spiral structure in galaxies and its relation to interstellar gas are reviewed. The evidence for spiral modes and resonance features in two-arm grand design galaxies is summarized. Gas observations of the corotation regions of these galaxies are needed. Multiple-arm galaxies could have several modes simultaneously, or they could lack modes altogether because of insufficient wave reflection in the central regions; then the spirals could result from transient shear instabilities. Flocculent galaxies may have similar shear instabilities but only in the gas. The importance of variable boundary conditions for clouds that flow through spirals is emphasized. These boundary conditions, such as pressure, radiation field, tidal force, and so on, affect the internal structure and molecular fraction of a cloud, and they could influence the calibration coefficient for determining mass from the CO luminosity. The importance of gas observations beyond the optical disk is also emphasized, to elucidate the role of the outer Lindblad resonance on wave propagation, and to study the proposed low-density cutoff for star formation.

1. The Connection Between Gas, Stars and Spiral Structure

A discussion of the origin and nature of spiral structure can be useful at a conference on galactic dynamics and molecules if it addresses problems that have been unclear or unknown for a while but can be largely resolved today with a few dedicated surveys. Among the most important issues in galactic spiral structure are 1. the longevity of the spirals, i.e., whether they are moderately long-lived *modes* ("quasi-stationary spiral structure") or transient waves (wave packets that wrap up and change shape), 2. the locations of the resonances and the determination of pattern speeds, and 3. the various origins for different spiral morphologies. Modern observations of the gas can address these problems to an extent never before possible, and they can also give insight into the spiral triggering mechanisms of cloud and star formation on a galactic scale.

Spiral structure should also be viewed as an important part of the *environment* of an interstellar cloud, imposing time-dependent boundary conditions (i.e. pressure, radiation field, etc.) for the clouds that are observed. These changing conditions can affect the local CO-to-total mass calibration through the dependence of the size-linewidth relation on pressure, and they can affect the molecular fraction in individual clouds through its dependence on radiation field. The disruptive forces from galactic tides and from collisions with other clouds also depend on spiral phase, giving different degrees of self-gravitational binding and different stages of evolution for clouds inside and between the spiral arms (e.g., see Rand

F. Combes and F. Casoli (eds.), Dynamics of Galaxies and Their Molecular Cloud Distributions, 113–129.

and Kulkarni 1990; Wiklind, *et al.* 1990). Thus a basic knowledge of galactic spirals, and of how the general interstellar medium changes with spiral phase, is important not only for understanding galaxies, but also for making a proper interpretation of observations of the gas.

There is also a *dynamical* connection between gas, stars and spiral structure. The spirals affect the distribution and kinematics of the gas on a 10^8 year time scale as the gas reacts dynamically to varying gravitational, pressure and magnetic forces, and it affects the evolution of the gas on 10^9 to 10^{10} year time scales by regulating star formation and by transferring angular momentum to the outer regions. Moreover, the *type* of spiral structure that a galaxy is *allowed* to have depends on the internal distribution of the stellar, *gaseous* and dark halo masses, and on the stellar and *gaseous* velocity dispersions in the disk. The type of spiral that it *actually* has at any particular time depends also on the recent history of internal and external perturbations. These perturbations range from the obvious, such as other galaxies or bright bars, to the imperceptible, such as giant *gas clouds* at the corotation resonance or an invisible triaxial halo.

Recent progress in understanding the connection between gas and spiral structure comes from the first detailed maps of HI, H_2 and star formation in nearby galaxies (Tacconi and Young 1990; Casoli, *et al.* 1990; see Viallefond, this conference). These maps show a large scale compression of the gas and magnetic field (Ondrechen 1985; Beck, *et al.* 1989) in spiral arms, with star formation in or around giant clouds that are lined up in a more-or-less regular fashion along the arms (Rand and Kulkarni 1990; Lo, this conference). The gas is also usually observed to be streaming along the arms in a manner consistent with the presence of a density wave (Rots 1975; Vogel, *et al.* 1988; Rydbeck, this conference). The extent to which the star formation rate per unit gas mass differs between the arms and the interarms is not yet clear (Elmegreen and Elmegreen 1986; McCall and Schmidt 1986; Giuricin, *et al.* 1989; Kennicutt 1990; Lord and Young 1990). Nevertheless, the basic theoretical concept that cloud and star formation follow gas cloud collisions, energy dissipation, and large scale gravitational collapse inside, and to a lesser extent, between spiral arms, seems to be consistent with the observed distribution of matter (Elmegreen and Elmegreen 1983a; Scoville, *et al.* 1986).

Recent progress in understanding the *origin* of the spirals in grand design galaxies comes from theoretical work on wave modes (Bertin, this conference) and wave-orbit resonances (Contopoulos, this conference), and from reasonably convincing evidence for modes in such galaxies (§2), along with the identification of optical features that may indicate the locations of resonances (§3). The origin of the structure in *multiple arm* and *flocculent* galaxies (§4) is probably understood in general terms also, although the variety of processes that can lead to such structures, including transient and independent spiral waves from gravitational or viscous forces (e.g., Carlberg and Freedman 1985; Fridman, *et al.* 1987), multiple modes that interfere (e.g., Considère and Athanassoula 1988; Lin and Lowe 1990), and pure star formation (Seiden and Schulman 1990), makes the identification of any dominant process for individual galaxies difficult at the present time.

Several suggestions for future observations are discussed in §5. These include a summary of ways to search for spiral resonances in the gas, a discussion of the expected arm-to-interarm variations in the properties of individual clouds and in the CO-to-H_2 calibration coefficient, and a comment on why the star formation rate appears to have a cutoff below a minimum gas column density.

2. Observations of Spiral Wave Modes in Galaxies

The difference between a wave and a wave mode in a galaxy is analogous to the difference between a travelling wave packet in a circular basin, such as a concentric pattern of ripples that expands away from the point of impact of a drop, and a *standing wave pattern* that sloshes all of the water up and down in a regular fashion, without any sideways motion of the crests and troughs. It is easy to make an expanding pattern of concentric ripples in a water basin -- any perturbation will start it -- but it is difficult to get the whole basin of water to oscillate coherently in a mode. A growing mode in a resonant cavity requires the application of a periodic perturbation at the right position and frequency, so the moving wave packets that

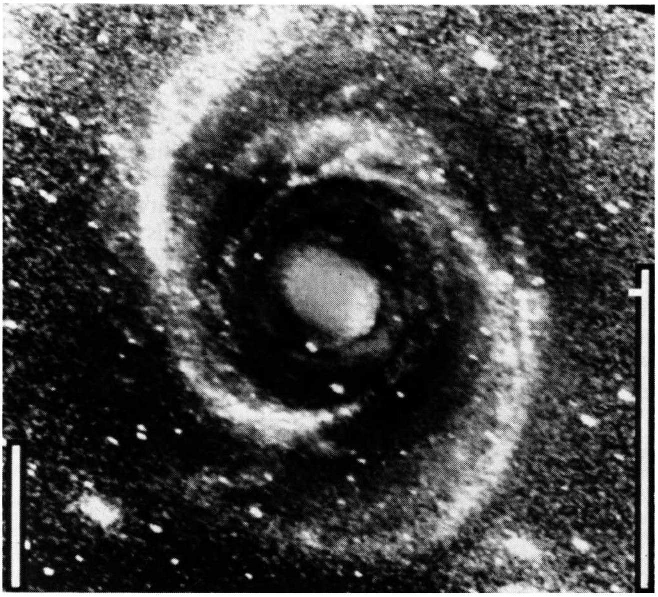

Figure 1. A rectified and enhanced version of the blue image of M81.

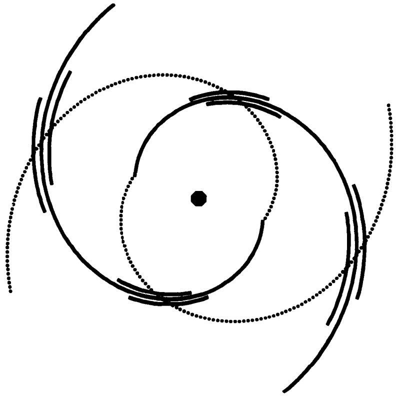

Figure 2. A schematic diagram of the spiral and reverse spiral patterns in M81.

result from the perturbation can reflect off the sides and return to the starting point in exactly the same phase as the perturbation has at that later time.

Similarly, a spiral wave in a galaxy requires only an initial perturbation, which can usually be small because of the subsequent amplification from self-gravity (the "swing amplifier;" Goldreich and Lynden-Bell 1965; Toomre 1981). A wave mode in a galaxy requires not only a perturbation, which can be small in this case too, but also some reflection or refraction in the central region, allowing the wave to return in exactly the right phase to the point of its amplification, which is corotation (Lin 1970, 1983; Mark 1976; Bertin 1983).

Computer models of galaxy disks have only recently been able to sustain a coherent self-similar wave for more than ~5 pattern revolutions at the same pattern speed (Thomasson, *et al.* 1990). All previous computer models either lacked sufficient amplification of the m=2 spiral compared to higher-m spirals, or lacked a sufficiently strong reflecting barrier in the inner region (outside the inner Lindblad resonance). Then the resulting spirals were always transient, with lifetimes of around one pattern revolution, whether they were multiple arm or grand design (see the review of transient spiral models in Sellwood 1989).

The nearby galaxy M81 may have a wave mode. This is inferred from the alternating and symmetric pattern of bright and dark areas in the arms, which are presumably the interference patterns from wave packets simultaneously travelling outward and inward in the disk. An enhanced image of M81 showing this alternating pattern is in Figure 1 (Elmegreen, Elmegreen and Seiden 1989), and a schematic diagram of the superposed spiral and reverse spiral waves is in Figure 2 (Elmegreen 1990a), with triple lines at the intersection points representing the locations of brightness maxima in the arms (compare to Figure 1). The m=2 part of this pattern has recently been fit to a theoretical modal solution for conditions appropriate to M81 (Lowe, *et al.* 1990). M81 may also have a strong m=3 component, as shown in Figure 3 by the *antisymmetric* part of the enhanced image (see Elmegreen 1990a).

Figure 3. The antisymmetric part of the blue band image of M81.

Other Fourier components for this galaxy were shown by Considère and Athanassoula (1988).

The grand design galaxies M100, M51, and NGC 1566 may have simple modes too, although no theoretical fits to the observed arm structures have been made yet. The presence of an m=2 mode in each galaxy is inferred from the appearance of a *global pattern of resonance phenomena,* such as spurs at the presumed inner 4:1 resonances, spiral arm termination points at the outer Lindblad resonance, and so on (see §3). Such resonances would seem to require several pattern revolutions to provoke a visible response in the gas and stars, implying that when they are found, the pattern has been present in about the same form for at least 10^9 years.

If these and other grand design galaxies do indeed have modes, and not just rapidly evolving spirals, then there would seem to be several important implications. The first is that the galaxies must have an *intrinsic* combination of properties that allow a mode to exist (see Bertin, *et al.* 1989; Thomasson, *et al.* 1990). For example, they may have relatively massive disks (in terms of the disk to halo mass ratio, when compared to flocculent and multiple arm galaxies), as suggested by falling rotation curves in grand design galaxies (D. Elmegreen and B. Elmegreen 1990), or they could have a kink in their rotation curves (Fridman, *et al.* 1987). They should also have an inner reflecting barrier, which for M81 and M100 appears to result from the bulge (cf. Lin 1970), and for M51 and NGC 1566 appears to be a small bar or oval near the ILR.

A second implication is that whatever started the *current* mode, whether it is now visible (e.g., a passing galaxy) or invisible (e.g., dwarf companions or now-dispersed gas clouds in the disk), the initial perturbation from this object did not have to be large for the whole disk to respond as it did. Most of the response is from the internal gravity in the disk, which gets many opportunities to amplify an initially small spiral as the wave reflects back and forth. The e-folding time of the spiral amplitude is approximately one galaxy revolution time (Bertin, *et al.* 1989), as confirmed by the numerical simulation (Thomasson, *et al.* 1990). Amplification factors of over 100 are possible for reasonable spiral lifetimes.

This allowed weakness of the initial perturbation should be kept in mind when studying computer simulations of galaxy interactions. It may be found, for example, that collisions which trigger spirals in galaxies that *can* support a mode are allowed to be so weak that the interaction generally does not lead to coalescence, or to major warps or disk heating, but that collisions which produce global spirals in galaxies that *cannot* support a mode may have to be so strong that the companion has a high probability of coalescing or driving a warp (e.g., see Barnes, this conference for a discussion of coalescing collisions, and see Brouillet, this conference for a discussion of models for the M81 group).

This distinction between spiral mode and spiral wave-packet triggering by companions is also important for non-barred grand-design spiral galaxies with remote group companions, such as NGC 628 (which is non-barred) and its possible triggering companion NGC 660. Such pairs often have a minimum time between closest approach of some 2×10^9 years, or ~10 rotations (Elmegreen and Elmegreen 1983b, 1989a). This seems to imply that the two-armed spirals are relatively long-lived if they were triggered by a previous interaction.

3. Optical Identifications of Wave-Orbit Resonances

Lin and Shu (1967) predicted that spiral arms should end at the outer Lindblad resonance (OLR), but for a long time there was some concern that a wave starting in the inner disk could not get out as far as the OLR because it has difficulty propagating through the corotation (CR) resonance when the disk is reasonably stable (it has to tunnel through a CR barrier; see Toomre 1977). As a result, the outer parts of spiral galaxies were thought to lie well inside the OLR, near or slightly inside the CR resonance (Roberts, *et al.* 1975). For a flat rotation curve, CR is inside the OLR by a factor of ~0.6 in radius. A similar concern arises today for strong waves, because the inner 4:1, 6:1, etc., resonances should scatter the stars when the spiral is strong (Contopoulos and Grosbøl 1986, 1988). Then the spiral should end at the inner 4:1 resonance, which is inside CR by another factor of ~0.6 in radius.

Bertin (this conference) suggests that tunnelling through CR should not be difficult if the gas in a galaxy is reasonably massive and if the gas can remain marginally unstable (i.e., cool) by heating and cooling processes (feedback) involving, for example, star formation and cloud-cloud collisions. Then a weak wave (relative potential < 10%) can extend from an inner reflection point or bar to the OLR, with the gas providing a major source of amplification at CR. Perhaps even strong waves with sufficient driving from cool gas can penetrate the 4:1 resonance barrier too.

If such penetration is possible, then essentially all of the most prominent optical spiral features in the galaxies M81, M100 and NGC 1566 can be explained in terms of resonance features and inner wave reflection barriers. This is discussed in detail in Elmegreen, Elmegreen and Seiden (1989) and B. Elmegreen and D. Elmegreen (1990). Table 1 summarizes the results for these three galaxies, and includes also the galaxy M51, which has

Table 1: Summary of Resonance Identifications

RESONANCE:	FEATURES AT RESONANCE:			
Galaxy:	M81	M100	M51	NGC 1566
ILR	inner extent of gas spiral	inner extent of gas spiral and an oval bar	inner extent of gas & star spirals, and a bar	inner extent of gas & star spirals, and a bar
Reflection?	Yes	Yes	No	No
4:1	spurs	spurs	spurs	spurs & 6:1 spurs
CR	?	SF ridge, circle of SF	SF ridge, bifurcation	SF ridge, circle of SF, bifurcation
OLR	end of stellar arms	end of stellar arms	edge of main disk & end of main arms	edge of main disk & end of main arms
MISC	-	-	tidal arms	elliptical ring between OLR and 1:1

several sensible resonance identifications too. Note that the main spirals end at the OLR. This termination radius was also found for five other galaxies by Athanassoula, *et al.* (1987), who used the constraint that the peak amplification of the m=2 wave should lie near the corotation radius.

In the three galaxies with high gas abundances (M51, M100 and NGC 1566), corotation is apparently indicated by an end to the sharply defined dust lanes and star formation ridges on each side of the galaxy. No star formation ridges or dense dust lanes are present in M81 because of its relatively low gas abundance. Two of the galaxies (M81 and M100) have their main stellar spirals wrap into a circle in the inner region (at about 0.35 R_{25} and 0.2 R_{25}, respectively) at what are presumably reflection points resulting from high $Q = \kappa c/\pi G\sigma$ values in the inner disks (κ is the epicyclic frequency, c is the velocity dispersion, G is the gravitational constant, and σ is the mass column density in the disk). The other two galaxies have stellar spiral arms that extend all of the way in to small ovals or bars in the nuclei. Perhaps these ovals or bars, which are near the inner Lindblad resonances (ILR), remove the need for an inner reflecting Q barrier. The other main resonances are also given in the Table. Spurs that are located exactly midway between the main arms (although they extend into the main arms) denote the 4:1 resonances in these solutions. Note that there is very little freedom in placing these resonances; once one is assumed, all of the others follow from the rotation curve. When all of the resonances match sensible optical features, as in the four galaxies here, then the pattern speed would seem to be reasonably well constrained.

The corotation radius in a galaxy may also have a signature in the star formation efficiency, which should have a local minimum at corotation if the spiral arms significantly trigger star formation via a shock front. Cepa and Beckman (1990) measured this efficiency using Hα and HI observations, and determined the arm to interarm ratio of the efficiency as a function of galactocentric radius. They found for NGC 3992 and NGC 628 that the arm/interarm efficiency ratios have three minima, and that the radii of these minima correspond well to the inner and outer Lindblad resonances and the corotation resonance, provided the pattern speed is chosen appropriately. The interpretation of the efficiency minima as an effect of triggered star formation may not be straightforward, however. The galaxies NGC 4321 and NGC 1566, for example, have much interarm star formation near the presumed corotation resonance (i.e., the circle of star formation discussed in Table 1). This interarm star formation may result from wave-independent processes in a region where the gas is not swept up by the spiral, as it is at other radii. With such independent processes operating (possibly in addition to direct spiral triggering processes), a minimum in the arm-to-interarm efficiency ratio may result from either a *decrease* in the *arm* efficiency or an *increase* in the *interarm* efficiency. In either case, the corotation resonance might still be located by this method, or by refinements of the method which include H_2 in addition to HI.

The importance of finding symmetrically placed resonances in a grand design galaxy is that it suggests that the spiral is relatively long-lived and it gives a pattern speed. Resonances also have predictable kinematic and star formation features, which would be interesting to observe (§5.1). The inferred extension of the spirals out to the OLR also suggests that the spiral potential is not so strong that the stars fail to reinforce it beyond the 4:1 resonance. Perhaps the 4:1 resonance acts as a source of wave damping (Artymowicz and Lubow, this conference), and prevents the destruction of spirals found by Contopoulos (this conference).

4. Multiple Arm and Flocculent Galaxies

Most galaxies in normal environments (i.e., in groups, clusters and in the field) are multiple arm or flocculent. In a size-corrected sample of 654 spiral galaxies from the Revised Catalogue of Galaxies (de Vaucouleurs, *et al.* 1976), Elmegreen and Elmegreen (1989b) found that approximately 10% are grand design while ~60% and ~30% are multiple arm and flocculent, respectively (depending on bar and Hubble type). This low fraction of grand design galaxies is consistent with the idea (§2) that a galaxy must have the proper distribution of mass and velocity dispersion in order to support a mode (if indeed most grand design galaxies are modes).

Figure 4. The symmetric part of the blue band image of M101.

Multiple arm galaxies have stellar spiral waves, as shown by near-infrared components underlying the optical spirals, but flocculent galaxies may not (or, if they do, they are very weak; Elmegreen and Elmegreen 1984). Perhaps the distinction between flocculent, multiple arm, and grand design galaxies is that flocculent galaxies do not have stellar waves, multiple arm galaxies have stellar waves but no simple modes, and grand design galaxies have modes. Multiple arm galaxies may have unshielded inner Lindblad resonances, in which case the waves may not reflect efficiently in the inner regions. Multiple arm galaxies might also have several modes, or high-order modes (e.g., Considère and Athanassoula 1988). M101 is a multiple arm galaxy with a strong m=4 component, as shown by the symmetrized, enhanced image in Figure 4 (note the four-cornered symmetry). In contrast, flocculent galaxies may have such high values of the stellar Q parameter that *stellar* spirals are impossible (or very weak), but the *gas,* with its lower Q value, can still have little spirals (Elmegreen and Thomasson 1990; see also Bertin, this conference) or pure star-formation spirals (Seiden and Schulman 1990). An example of a flocculent galaxy is NGC 5055, shown rectified and enhanced in Figure 5a. A symmetrized version of this image (Figure 5b) reveals weak and short m=2 arms.

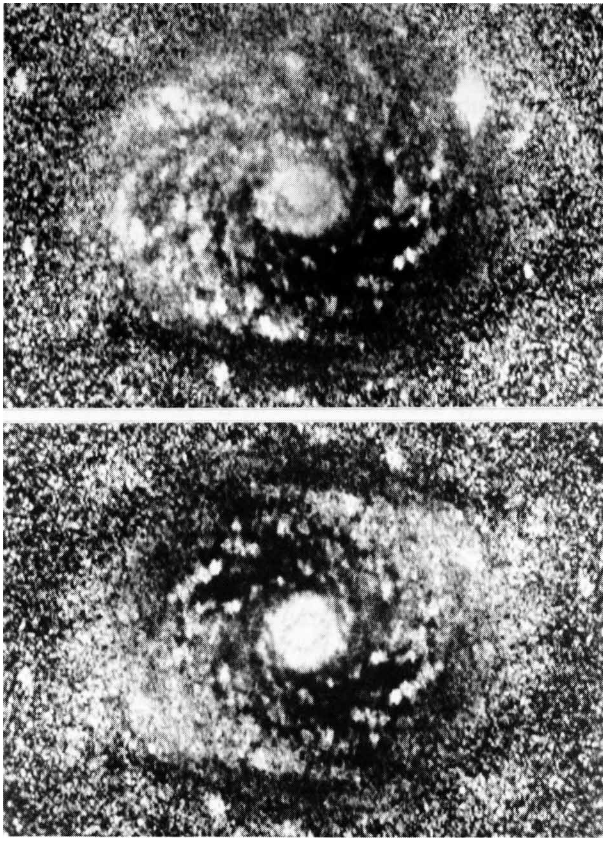

Figure 5. (a-top) A rectified and enhanced version of the blue band image of NGC 5055; (b-bottom) the symmetric part of the image in (a).

5. Implications for Molecular Cloud Dynamics and Distribution

5.1. RESONANCES

Molecular and atomic gas observations of galaxies can help to determine many of the properties of spirals. Observations of the velocity distribution can locate the corotation resonance at the radius on the minor axis at which the streaming motion of the gas in the arms shifts from inward at smaller radii to outward at larger radii. This position should also be where the streaming motion *between* the arms shifts from outward at smaller radii to inward at larger radii. Such a shift may be found on diagrams of the local velocity minus the systematic velocity from the average rotation curve; the shifts may not show up well on contour or color plots of total velocity, which are dominated by systematic rotation. The occurrence of velocity shifts at corotation may be limited to grand design galaxies, which have relatively simple patterns and single (or, at least, a small number of) corotation radii.

One problem with this method of determining the CR radius is that, although CR is not expected to be at the far outer edge of the spiral, the CR radius is still in a region of relatively weak disk emission, at some 2 to 2.5 exponential scale lengths from the center. Thus the observation of streaming motion shifts may be difficult if optical (Hα) or CO emissions are used. To overcome this problem, the search for CR could begin with strongly barred galaxies, which may have CR near (i.e., slightly beyond) the ends of the bars; this region is still relatively bright. A problem here is that the pattern speeds for the bar and the outlying spirals may differ (Sellwood and Sparke 1988), especially for late Hubble types (Elmegreen and Elmegreen 1985; 1989b), in which case the CR zone of the spiral may still be in the faint outer disk. Perhaps some of the features listed in Table 1 or the method of Cepa and Beckman (1990, see above) could be used to locate CR optically, and then the streaming motion shifts might be found more easily.

Radio observers should also look for spirals in the HI or CO emission *beyond* the optical disk. Theory allows the spirals to continue in the gas beyond the outer Lindblad resonance, even if the stellar spirals stop there, but the outer gaseous arm amplitudes might be small. The outer gas spirals may also have a small amount of star formation. Such a study of outer disk gas should be limited to non-interacting galaxies if the purpose is to test the influence of the OLR on the gas and stars in the main disk. If there is an obvious companion, then outer gas arms could be tidal in origin, and not driven directly by the inner spirals.

A third observation is to measure the properties of the dust lanes in spurs, which are tentatively identified with inner 4:1 resonances (except perhaps for the four spurs near corotation in M51, see above). Optical studies of such spurs are in Elmegreen (1980a,b). The shock compression may be larger in the 4:1 spurs than in the main arms because of the higher pitch angles in the spurs.

5.2. PRESSURE AND RADIATION FIELD VARIATIONS

One of the most important reasons why observers of molecules in galaxies should be concerned with spiral structure is that the boundary conditions for clouds vary greatly with the phase of the spiral. In the spiral arms, the pressure, magnetic field strength, and ambient radiation field should be higher (even before or without star formation), and the shear and galactic tidal forces should be lower, than in the interarm regions. These variations should apply to both grand design and multiple arm galaxies. The relative variations of these quantities through the arms of flocculent galaxies is unknown, but if flocculent arms are purely gas and young stars (Seiden and Schulman 1990), then the local shear and tidal forces may not change much from the arm to the interarm regions.

Interstellar pressure should also vary with radius in a galaxy. If the interstellar gas satisfies the equation of hydrostatic equilibrium, then

$$P = \frac{\pi}{2} G\sigma_g(\sigma_g + \frac{c_g}{c_s}\sigma_s)$$

where G is the gravitational constant, σ_g and σ_s are the mass column densities of the gas and stars in the galactic disk, and c_g and c_s are the local velocity dispersions (including magnetic effects) of the gas and stars (Elmegreen 1989). Additional variations in pressure could come from transient effects (i.e., before the scale height adjusts) in a shock front. The interstellar pressure should also vary from galaxy to galaxy, although perhaps not by much in normal galaxies because of the Tully-Fisher relation (which says that the total mass column density is relatively constant from galaxy to galaxy), but pressure could be very large in the inner regions of starburst galaxies. The pressure is also expected to be temporarily large in spiral arm dust lanes and in the vicinities (100 to 300 pc) of OB associations (see Ikeuchi 1988).

The pressure boundary for a molecular cloud is usually ignored in discussions of molecular cloud structure and dynamics because the internal or average cloud pressure is much larger than the ambient interstellar pressure when gravity is strong, as in a star-forming cloud. Even in the virial theorem, where the boundary pressure should enter, it has been fairly safe to ignore this pressure for most clouds because of competing effects from internal magnetic fields, which are also usually ignored in the evaluation of the coefficients. These competing effects conspire to give about the same coefficient in the virial theorem relation between mass, radius and velocity dispersion when both magnetic fields and boundary pressure are included as when no magnetic field or boundary pressure are included. But boundary pressure is important -- even if its presence in the virial theorem is not obvious. The boundary pressure controls, in part, how a cloud moves, especially if the clouds are interacting magnetically. The boundary pressure also helps to determine the thickness and column density of the HI/H_2 shielding layer (Elmegreen 1989). High pressure regions should be more completely molecular even if the clouds are diffuse and have no connection to star formation.

The influence of ambient pressure on internal cloud structure depends largely on the dimensionless quantity $\hat{P} = P/(G\sigma_c^2)$ for pressure P and mass column density of a cloud σ_c. This quantity is of order 1 or larger for diffuse clouds, and it is much less than 1 (e.g., 0.01) for strongly self-gravitating clouds. Both diffuse and self-gravitating clouds can be molecular, but the flow pattern (ballistic versus hydrodynamic), degree of clumpiness, and connection with star formation should differ for gas components with greatly different $\hat{P}$. Thus a given cloud can significantly change its structure when the pressure of its environment changes.

The influence of pressure on molecular (H_2) self-shielding can be estimated as follows. A molecular cloud at moderate-to-high average densities (> 10 cm^{-3}) shields itself by line absorption (not dust absorption) in the photodissociative transitions. The total absorption rate at a cloud surface therefore scales with the molecule formation rate integrated over the surface depth. This integral is proportional to n^2RZ for root mean squared density n, radius R and metallicity Z. In a shielding layer, the molecule formation rate is equal to the photodissociation rate, which is proportional to the ambient radiation field, ϕ, corrected slightly for cloud column density, as $N^{1/3}$ for example, to account for absorption in the line wings (Federman, *et al.* 1979). The ratio of these quantities is a *shielding function*

$$S = \left(\frac{n}{60\mathrm{cm}^{-3}}\right)^{5/3}\left(\frac{R}{1.4pc}\right)^{2/3}\frac{Z/Z_\odot}{\phi/\phi_\odot}$$

which determines the degree of self shielding. When $S > 1$ a cloud should be mostly molecular and when $S < 1$ a cloud should be mostly atomic. The calibration in the expression for S is from Copernicus observations of H_2 molecules in diffuse clouds. Calibration for dense molecular clouds is not yet known. Note that this expression applies primarily to H_2 molecules, and not CO.

For a spherical, magnetic, self-gravitating, polytropic cloud having a value of $\hat{P}$ that covers a wide range (0.006 - 0.1), the average boundary density n and radius R in the above expression for S may be converted into a boundary pressure P and mass M because P scales with $G\sigma_c^2$ so $n \propto P^{1/2}/R$ and $R \propto M^{1/2}/P^{1/4}$ (for $\sigma_c \propto M/R^2$); thus $n^{5/3}R^{2/3} \propto nN^{2/3} \propto P^{13/12}M^{-1/2}$. In the more detailed analysis (Elmegreen 1989), the result is

$$S = 1.2\left(\frac{P}{10^4 k_B\ \mathrm{cm}^{-3} K}\right)^{13/12}\left(\frac{M}{10^5 \mathrm{M}_\odot}\right)^{-1/2}\frac{Z/Z_\odot}{\phi/\phi_\odot}.$$

This equation implies that clouds of a given mass should be more completely molecular in regions of high pressure or metallicity, or low radiation field. Conversely, where the radiation field is high, as in the crest of a bright spiral arm, the molecular fraction should be lower (i.e., the clouds turn atomic -- see Tilanus and Allen 1989). The equation also suggests that for given P, Z, and ϕ, the *largest self-gravitating clouds should be mostly atomic.* This latter result, although surprising at first, follows from the near constancy of σ_c for a virialized cloud at a given boundary pressure, in which case n is smaller, and self-shielding is more difficult, for large M. This explains why the largest self-gravitating clouds in the Milky Way are mostly atomic (McGee and Milton, 1964; Elmegreen and Elmegreen 1987), or contain substantial amounts of low density, "diffuse" molecular gas (Polk, *et al.* 1988), whereas similar giant clouds in M51, where the average interstellar density and pressure are larger than in the Milky Way, are mostly molecular (Rand and Kulkarni 1990). The giant clouds in NGC 6946 may be an intermediate case, similar to the diffuse molecular clouds in our Galaxy, because much of the CO emission apparently comes from the low density envelopes of cloud complexes (Casoli, *et al.* 1990).

The dependence of S on $P^{1.1}Z/\phi$ may also explain why Young and Knezek (1989) found slightly higher molecular abundances in early type galaxies compared to late types. Early type galaxies generally have large total mass column densities and may therefore have slightly higher midplane pressures and metallicities, along with lower radiation fields, than late type galaxies. Note that a high $P^{1.1}Z/\phi$ can turn an atomic diffuse cloud into a molecular diffuse cloud, so the high abundance of molecules in early type galaxies may result from a higher relative abundance of *diffuse* molecular clouds ($\hat{P}\sim 1$) and have no direct relation to star formation, which takes place in strongly self-gravitating clouds ($\hat{P} << 1$).

5.3. THE CO/H$_2$ CALIBRATION RATIO

Radiation field and gas temperature variations in spiral density waves may affect the calibration coefficient for converting molecular luminosities into gas masses. If we consider the pressure at the molecular cloud boundary and write this in terms of the total boundary pressure at the edge of the cloud, P, considering the weight of the overlying H-H$_2$ shielding layer, then the ratio of the average molecular column density through a cloud (i.e., out to the molecular boundary) to the integrated CO line strength may be derived from the virial theorem, and is nearly independent of pressure and mass for a wide range of polytropes (Elmegreen 1989):

$$\frac{N_m(\mathrm{H}_2)/\mathrm{cm}^{-2}}{W_{CO}/\ \mathrm{K\ km\ s}^{-1}} = 2.3\pm0.6\times10^{20}\left(\frac{T}{4\mathrm{K}}\right)^{-1}\left(\frac{P}{10^4\ \mathrm{k}_B\mathrm{cm}^{-3}\mathrm{K}}\right)^{-1/32}$$
$$\times\left(\frac{M}{10^5 \mathrm{M}_\odot}\right)^{-1/16}\left(\frac{\phi/\phi_\odot}{Z/Z_\odot}\right)^{3/8}.$$

This ratio has important dependences on the radiation field ϕ and the area-averaged cloud brightness temperature, T, both of which could vary by factors of 2 to 10 between the arm and interarm regions. This result implies that molecular cloud masses could be overestimated or underestimated in the interarm regions if $\phi^{3/8}/T$ is low or high there, respectively, compared to the value for spiral arm clouds which are generally used for calibration. The interarm clouds could also be more diffuse than the arm clouds because of disruption from star formation and increased tidal forces (see Wiklind, *et al.* 1990).

Another important consideration for the molecular cloud mass calibration is that the coefficient in the ratio M/L_{CO} for an ensemble of unresolved clouds in a galaxy equals the calibration coefficient for a single cloud multiplied by $(2.25 - \alpha)/(2 - \alpha)$, where α is the slope in the cloud mass spectrum $n(M)dM \propto M^{-\alpha}dM$. For typical $\alpha = 1.5$, this factor equals 1.5. The extra factor enters because the H_2 mass does not scale directly with CO luminosity, but with $L^{4/5}$ (Solomon, *et al.* 1987), which also follows from the virial theorem (Elmegreen 1989). Considering this virial relation, the mass-to-luminosity ratio for a whole galaxy (or for a piece of a galaxy containing several unresolved clouds) divided by the calibration coefficient, which is the mass column density to integrated line profile ratio for individual local clouds, is given by the equation (Elmegreen 1989):

$$\frac{(M[\mathrm{H}_2]/L_{CO})_{gal}}{(m[\mathrm{H}_2]N[\mathrm{H}_2]/W_{CO})_{local}} =$$

$$1.5\left(\frac{T_{local}}{T_{gal}}\right)\left(\frac{P_{local}}{P_{gal}}\right)^{1/32}\left(\frac{M_{local}}{M_{gal}}\right)^{1/16}\left(\frac{G_{gal}/G_{local}}{Z_{gal}/Z_{local}}\right)^{3/8}.$$

If extragalactic clouds are identical to galactic clouds, then the molecular surface densities of galaxies should be a factor of 1.5 larger than what is usually estimated using the calibration coefficient for single clouds; i.e., galaxies may contain 50% more molecular mass than what is usually derived.

5.4. WHY DOES STAR FORMATION REQUIRE A THRESHOLD GAS COLUMN DENSITY?

Guiderdoni (1987) and Kennicutt (1989) found that star formation in a galaxy stops when the total gas column density drops below a threshold. These studies, and also Kennicutt (1990), suggested that this threshold scales with the critical column density for gravitational instability, as determined by the $Q = \kappa c/\pi G\sigma \sim 1$ condition discussed above. This follows from the idea (e.g., Quirk 1972) that large-scale gravitational instabilities initiate star formation.

The actual processes that initiate star formation on a large scale are very uncertain, however, as is the basic stability of the gas layer in a galaxy. *Gas* disks with *magnetic fields* should not necessarily have a sharp Q threshold between stable and unstable regions; instead, a large Q may only lead to a slower unstable growth, but not stability (Lynden-Bell 1966; Elmegreen 1987, 1990b). For example, HI observations of the far-outer parts of the spiral galaxy NGC 6946, beyond the visible disk (Boulanger and Viallefond 1990; see also Viallefond, this conference), show giant cloud complexes similar to those in the inner parts of this galaxy, with scales comparable to the Jeans length, but there is no perceptible star formation there. This seems to imply that gravitational instabilities occur even in the remote regions, but that such instabilities do not always lead to star formation.

There are several reasons why star formation may be slow or suppressed in the outer regions of galaxies. When the density is very low, the energy dissipation rate can be less than both the instability rate and the spiral arm flow-through rate. Then "superclouds" can form in the spiral arms (where the shear is low -- Elmegreen 1987; see also Waller, this conference) at the instability rate, but they cannot condense further into high-density, star-forming cores (at the dissipation rate) before they emerge from the arms and get disrupted by large tidal forces in the interarm regions. The time scales for these processes are compared for various spiral arm strengths in Elmegreen (1988). An increase in the gaseous scale height (e.g., a flare in the outer disk) might also slow down star formation. Unfortunately, very little is known about the outer parts of galaxies, including the state of stability of the gas and the magnetic field structure.

The properties of the stellar spirals near the outer optical edge of a galaxy are also important for star formation. For the four galaxies in Table 1, the outer edge, near R_{25} (the radius at 25 magnitudes per square arc second), is within 10% of the radius of the outer Lindblad resonance, where the main stellar spiral stops. Beyond this radius, the gas should not be significantly compressed by a *stellar* density wave (although there can still be gas spirals in the far outer disk - see Viallefond, this conference). If density wave compression (and the corresponding decrease in shear, for example) is responsible for star formation, then a sharp outer cutoff in the star formation rate may be the result of a termination of the main spiral pattern, and not a drop below threshold of the column density. Here again, the consideration of spiral structure affects even the most fundamental interpretation of observations of the gas and star formation.

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