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FROM GAS TO STARS: REGULATION OF STAR FORMATION

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1. Introduction

Understanding the physical processes that govern the conversion of interstellar gas into stars is crucial for a host of fundamental problems: galactic structure, the nature of the Hubble sequence, galaxy formation and evolution, and chemical evolution. Although our understanding of large-scale star formation and its relationship to the interstellar medium (ISM) is at a primitive state, a recent flurry of observations and theoretical modelling has provided important new insights into the star formation law and its physical basis.

The roots of this field trace to the seminal paper of Schmidt (1959), which introduced the star formation rate (SFR) vs gas density power law that is still used today. The Schmidt law is an adequate description for some aspects of the problem, but observations of nearby galaxies have revealed environments where a single power-law parametrization clearly breaks down. A significant breakthrough came with the observation of star formation thresholds, which when combined with a Schmidt law at high densities reproduces the wide range of star formation properties of galaxies. The tentative association of these thresholds with large-scale gravitational instabilities in the ISM provides a physical framework for the observed star formation law, and the beginnings of a quantitative model for global star formation in galaxies. Several important elements of this picture— the physical nature of the star formation thresholds, the physical regulation of the SFR above the threshold, and the role of feeback between stars and gas in the star formation law— remain poorly understood and are the focus of much current research.

In this paper I review recent progress in our understanding of the empir-

ical form and physical basis of the star formation law, and identify some of the key issues for future work. Section 2 reviews the successes and failures of the Schmidt law, with emphasis on those problems for which the Schmidt law *does* serve as a useful parametrization of the SFR. Section 3 summarizes recent work on star formation thresholds: observational evidence, the gravitational stability model, and the successes and failures of that model. The physical nature of these "star formation" thresholds is discussed in Sec. 3.4. While thresholds may provide physical insight into why stars stars do *not* form in galaxies, they leave unanswered the question of what controls the SFR at densities above the threshold. Section 4 reviews some recent ideas on this subject, with special emphasis on self-regulating models. For background material on earlier developments in this field I refer the reader to reviews by Larson (1987, 1988) and Kennicutt (1990).

2. The Schmidt Law

Thirty-five years after its introduction the Schmidt law remains as a useful parametrization of the SFR for many applications, and the basis of nearly all subsequent work. The original Schmidt (1959) law related the volume densities of young stars and gas in the Galactic disk:

$$\rho_{sf} = a\rho_{gas}^{n}$$

but for external galaxies, where projected densities are observed, it is conventional to adopt a surface density law:

$$\Sigma_{sf} = A\Sigma_{gas}^{N}$$

It is important to recognize the physical distinction between the observed and true (3D) laws. Fortunately in most environments the slope of the power law is small enough that the distinction is not crucial.

Since 1959 roughly 50 papers have been published which attempt to measure the value of N, by correlating the surface densities of a young Pop I stellar tracer with gas column densities. Compilations and discussions of this work can be found in Berkhuijsen (1977), Madore (1977), Freedman (1984), and Kennicutt (1990). My own updated compilation is summarized in Figure 1, which shows the distribution of derived values of N. The values cover a wide range, with a broad peak between $N = 0.8$ and 2.5 and a full range of $N = \pm 3.5$. This large dispersion can be attributed partly to observational factors, such beam smearing effects or fitting to only the atomic or molecular gas densities. However much of the scatter is real, being caused by such factors as deviations from a power law or spatial variations in N across a galaxy. The failure of this wide body of observations to

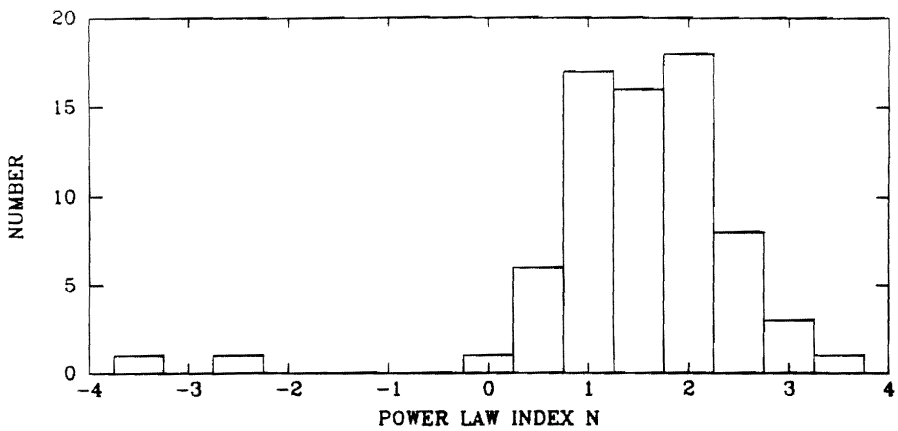

Figure 1. **Best fitting values of Schmidt law index N, from a compilation of the literature.**

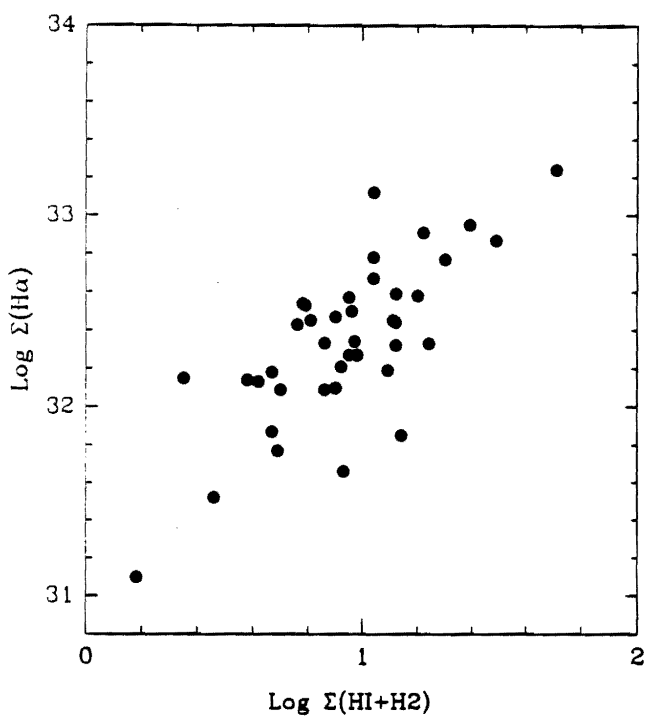

Figure 2. **Relationship between disk-averaged Hα surface brightness, proportional to the SFR per unit area, and average gas surface density for nearby spiral galaxies, from Kennicutt & Martin (1995).**

converge on a single Schmidt law is evidence in itself for the limitations of a power-law parametrization.

Nevertheless there are applications for which a Schmidt law *does* provide a useful description of the SFR, especially when applied to the integrated SFRs of galaxies. This is illustrated in Figure 2, which shows the relationship between the average Hα disk surface brightness and the average gas surface density (molecular and atomic) for a sample of nearby spirals (Kennicutt & Martin 1995). Each point represents a single galaxy, where the Hα intensities (which should scale with the SFR) and gas densities have been averaged over the optical diameter of the disk. Although there is considerable scatter in the relation, the correlation demonstrates that a Schmidt law with $N \sim 1.5$ provides a reasonable parametrization of the global evolution of disks.

Several authors have analyzed the dependence of the disk-averaged SFR on the molecular and atomic surface densities separately. For example Figure 3 shows the dependence of ultraviolet surface brightness, as measured by the FAUST experiment, on average total, H_2, and H I surface densities (Deharveng *et al.* 1994). The coupling between the SFR and molecular surface density is surprisingly weak, a trend that has been observed in several other studies (e.g., Buat *et al.* 1989, Kennicutt 1989, Buat 1992, Boselli 1994), and is probably related to variations in the CO/H_2 conversion factor. On the other hand, the SFR is tightly correlated with H I surface density, even though H I often comprises only a small fraction of the (mostly molecular) disk within the star forming radius. This raises the question of whether the SFR is being determined by the gas density, or whether it is the SFR which is regulating the H I density, for example via photodissociation of molecular hydrogen (e.g., Shaya & Federman 1987; Tilanus & Allen 1989; Knapen & Beckman, this meeting). This example illustrates the potential pitfalls in inferring causal relations from an observed correlation, without a full understanding of its underlying physical basis.

The Schmidt law provides a less deterministic description of the SFR on smaller physical scales. This is illustrated in Figure 4, which shows the correlation of Hα surface brightness on H I column density in cells of 220 pc in the LMC (Kennicutt *et al.* 1995). When the data are binned in column density a monotonic Schmidt law is apparent, with $N = 1.75 \pm 0.3$, consistent with previous studies (e.g., Tosa & Hamajima 1975). However the distribution of individual points is a virtual scatter diagram, with the correlation evident only when the data are binned. Compare this scatter with the relatively tight correlations in Figs. 2–3. Similar results were found in a study of M33 by Freedman (1984). These results suggest that the Schmidt law should be regarded at best as a statistical description of the star–ISM relation. The change in the character of the relation with physical scale

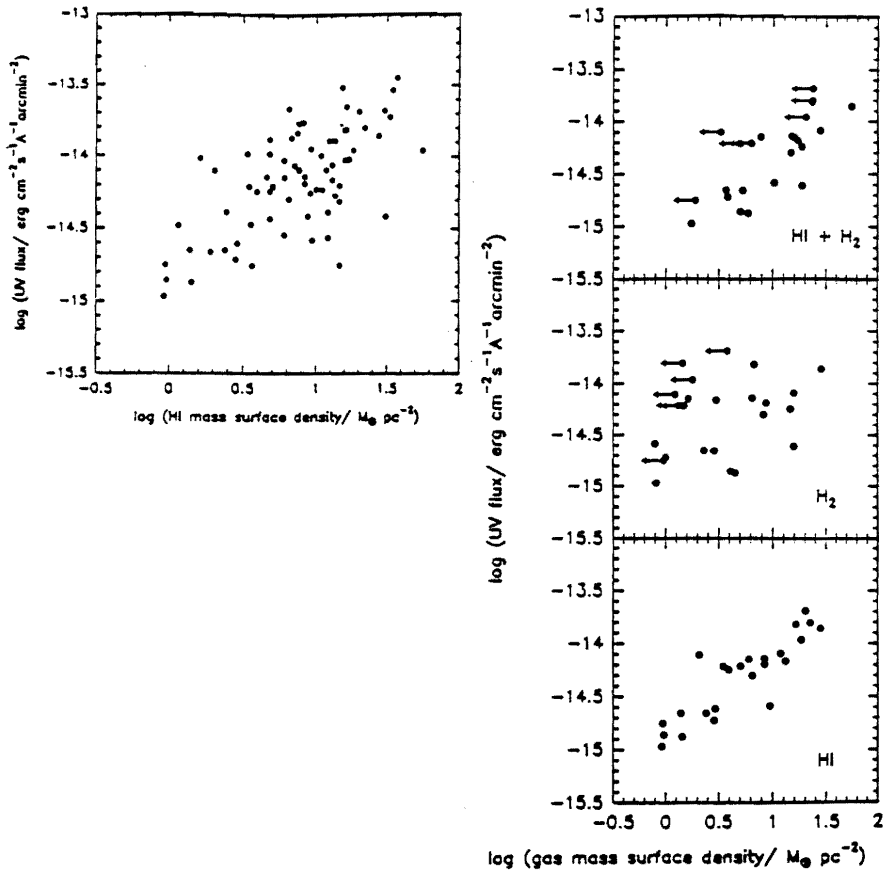

Figure 3. Correlation of mean UV surface brightness on gas surface density, showing the separate dependences on total, molecular, and atomic gas surface densities. From Deharveng *et al.* 1994.

should not be surprising, because the physical processes which underlie the observed law certainly change from the parsecs scale, where internal cloud processes (e.g., star formation efficiency) dominate, to galactic scales where large scale disk instabilities and cloud formation/destruction processes are most important.

There are several physical environments where the Schmidt law, if it applies at all, changes form radically under different conditions. The global SFRs in active star forming disks, for example, are governed by a relatively mild ($N \sim 1$–1.5) Schmidt law, as shown in Figures 2–3. The relatively slow evolution of the stellar birthrate in the solar neighborhood and in other disks also requires a weak dependence of SFR on gas density

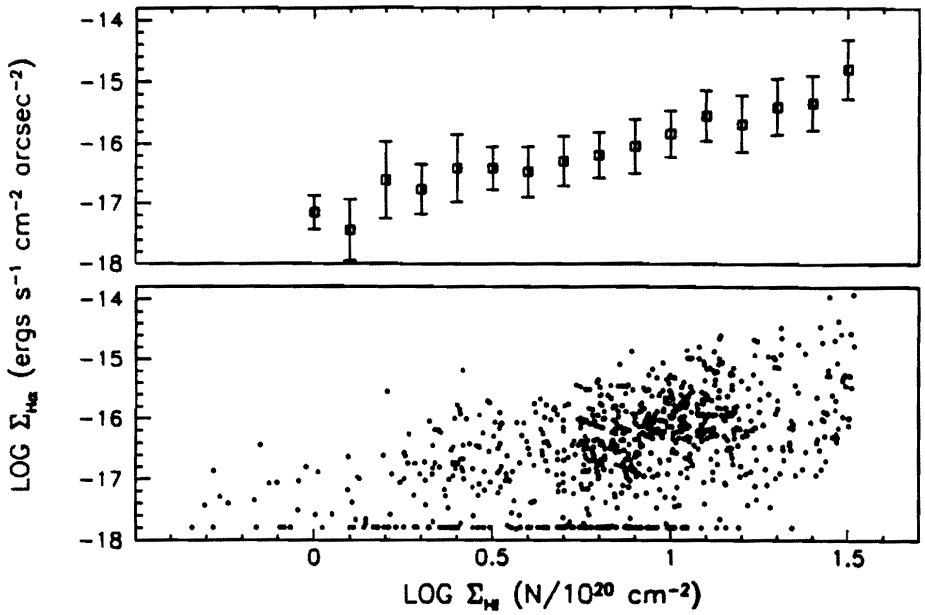

Figure 4. Hα vs H I correlation for the LMC. Points represent individual 220 pc cells, while the bars show mean trends when the points are binned in column density. From Kennicutt *et al.* (1995).

(e.g., Kennicutt *et al.* 1994). On the other hand, highly nonlinear ($N \gg 1$) Schmidt laws are needed to account for the orders-of-magnitude increases in the SFRs of starburst galaxies and interacting galaxies, or the strong arm-interarm constrasts in star formation observed in grand-design spirals such as M51 (e.g., Rand 1993). Similar nonlinearities are required to account for the *absence* of star formation in low surface brightness spirals or gas-rich S0 galaxies, which fail to form stars despite possessing gas masses that often are several times that of the Galaxy. This wide range of linear and nonlinear behaviors must hold an important clue to the physical processes which regulate the SFR. Fortunately a simple modification to the Schmidt law— the introduction of a Jeans-like star formation threshold— can account for this wide range of phenomena within a single quantitative framework.

3. Star Formation Thresholds

3.1. OBSERVATIONS

There is now extensive observational evidence that the SFR vs gas density relation turns over abruptly below a critical threshold value (e.g., Davies *et al.* 1976, Gallagher & Hunter 1986, Guiderdoni 1987, Skillman 1987,

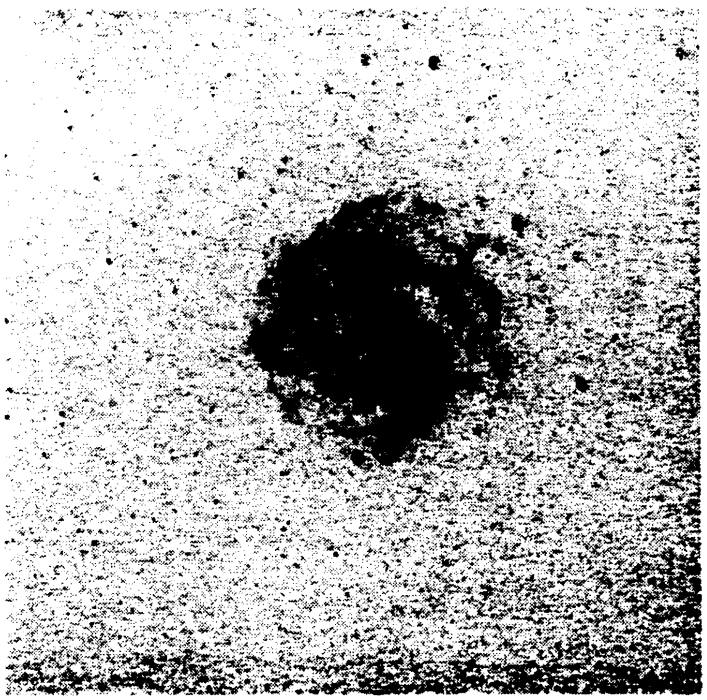

Figure 5. Deep Hα image of M83, showing sharp outer threshold to the star forming disk. The diameter of the Hα disk is $\sim$10$'$, compared to an H I diameter of 40$'$. The spots are large radius are artifacts of the foreground star subtraction.

van der Hulst *et al.* 1987, Kennicutt 1989, Taylor *et al.* 1994). A pictorial example is shown in Figure 5, which shows a high-contrast Hα image of the nearby SBc galaxy NGC 5236 (M83). There is nothing subtle about the threshold; an abrupt edge to the active star forming disk is evident, even though the H I extends to 3 times the optical radius (Rogstad *et al.* 1974). Sporadic star formation is often observed beyond the threshold radius, but at a level which is far below the extrapolation of the inner exponential disk. Often the threshold is abrupt, as in M83, but in other cases the transition region is spatially resolved. Usually the threshold occurs near the optical radius of the disk (R_{25}), but in some cases it extends to near the limit of the gas distribution (e.g., M101) and in others well inside the stellar disk (e.g., NGC 4736, NGC 4569). As discussed by Kennicutt (1989) there is no clear association of the Hα thresholds with the transition between a molecular and atomic-dominated disk, but the available observations are barely adequate to conduct such a test (see Sec. 3.4).

The effect of the thresholds on the observed star formation law is shown

in Figure 6, taken from Kennicutt & Martin (1995). The top panel shows the dependence of Hα surface brightness on (total) gas surface density, as measured in radial rings for several active star-forming galaxies. Note that galactocentric radius varies over the length of each profile, so factors other than gas density may be influencing the SFR. At high densities the relations follow a very rough Schmidt law with mean $N \sim 1.3$, but the SFR drops abruptly at the threshold density. The second panel shows the same relation for a sample of early-type spirals, with detectable but low SFRs across their disks. The SFR–density relation is much less well defined in this case, but note that the qualitative behavior of the law is similar to that seen in the threshold regime in the active star forming galaxies. The thresholds occur at surface densities of order a few $M_\odot$ pc^{-2}, or $\sim 10^{21}$ H cm^{-2}, but with a significant variation between galaxies, with roughly a tenfold range over the entire sample.

3.2. THE GRAVITATIONAL STABILITY MODEL

Kennicutt (1989) suggested that the observed star formation thresholds might be caused by large-scale gravitational instabilities in the gas disks. Such a suggestion is not new. Quirk (1972), Elmegreen (1979), Cowie (1981), Larson (1983), and Lacey & Fall (1985) explored the possibility of gravitationally-induced cloud or star formation thresholds, but insufficient data were available for a rigorous test of the model. Kennicutt (1989) tested the model using the stability criterion of Safronov (1960) and Toomre (1964):

$$\Sigma_c = \frac{\kappa c}{\pi G}$$

$$Q \equiv \frac{\Sigma_c}{\Sigma_{gas}}$$

where Σ_c is the critical surface density, κ is the epicyclic frequency at a given radius, and c is the velocity dispersion of the gas. This of course is an idealization of any actual threshold for instabilities in a realistic galactic disk, but it should at least approximate the actual criterion for any gravitational instability in regions where the disk rotation velocity is roughly constant (see Sec. 3.4). The observation that the gas velocity dispersion in disks is roughly isothermal (e.g., van der Kruit & Shostak 1984) allows us to apply the Toomre criterion with a minimum of free parameters. For a constant value of c the critical density scales as v/r, where v is the circular rotation velocity (constant over most of the disk) and r is galactocentric distance. Hence Σ_c falls off roughly as $1/r$ over most of the disk, and the SFR will be dictated by the relation of this decline to the actual radial density profile of the gas in the disk.

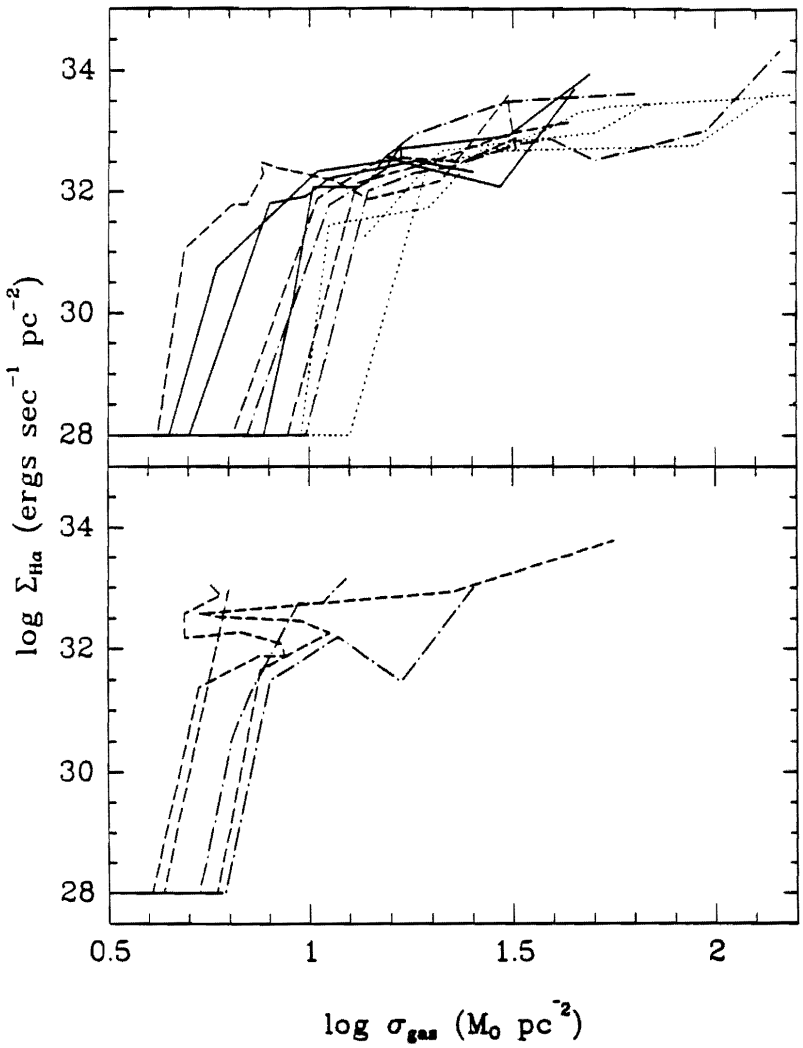

Figure 6. **Star formation laws for examples of active star forming galaxies (top) and relatively inactive early-type spirals (bottom), from a subset of the study of Kennicutt & Martin (1995).**

Kennicutt (1989) computed $\Sigma_c(r)$ and $Q(r)$ for ~20 galaxies with available Hα CO, H I data and rotation curves, assuming a constant gas velocity dispersion $c = 6$ km s^{-1}. Figure 7, taken from that paper, shows the radial run of $\Sigma_{gas}/\Sigma_c = Q^{-1}$ for the star forming galaxies (top) and early-type, low-SFR galaxies (bottom) in the sample. The radial coordinates are nor-

malized to the observed threshold radius (top) or optical radius (bottom). In the star forming galaxies (top) the Q criterion readily separates the regions of active star formation, and the curves all pass through the stability limit ($Q \sim 1.5$) near the observed threshold radii. The same Q criterion successfully explains the absense of global star formation in the early-type disks; in those few regions where $Q < 1.5$ rings of bright H II regions are observed. The deviation of the best fitting stability value from $Q = 1$ could be real or reflect an incorrect choice of the gas velocity dispersion.

The gravitational stability criterion provides a natural physical framework for interpreting the observed star formation law and the gas distributions in disks. One expects three distinct star forming regimes: 1) At high gas densities relative to the threshold ($Q \ll 1$) cloud formation proceeds without inhibition, and global star formation takes place; 2) In regions where $Q \gg 1$ cloud formation would be suppressed and only sporadic star formation, if any, should be present. This could occur in the outer regions of disks where the gas densities are low, or in the inner regions of galaxies where the threshold density is high; 3) In regions where $Q \sim 1$ the SFR will abruptly change from the unstable to stable regime. The slope of the star formation law should be very nonlinear, and cloud formation will be sensitive to local perturbations.

Over time the star formation acts to deplete the gas density until it approaches the $Q \sim 1$ stability limit. Hence a prediction of the model is that the radial distribution of gas surface density in most spiral disks should approximate a $1/r$ distribution near the stability limit. This in fact is observed (Figure 7), and hence the gravitational model provides a natural explanation for not only the distribution of star formation but also the distribution of gas in galaxies (Quirk 1972; Zasov & Simikov 1988). It also means that over most of the disk the gas lies in a quasi-stable regime, close to the transition between a roughly linear and highly linear Schmidt law.

3.3. OBSERVATIONAL TESTS OF THE Q MODEL

The Q model can be tested by comparing the observed threshold radii and surface densities in nearby galaxies with the values predicted from application of the Toomre criterion above. Such a comparison, for the galaxies shown in **Figure** 7, is shown in Figure 8 (Kennicutt 1989). Given the simple assumptions that went into the model (pure thin gas disk model, Toomre criterion, isothermal disk) the agreement is surprisingly good. We are currently repeating this analysis with a complete H I and CO-selected sample and better Hα data (Kennicutt & Martin 1995). In the meantime several investigators have tested the Q model with other types of galaxies.

Low surface brightness spirals (LSBs) and gas-rich S0 galaxies, with

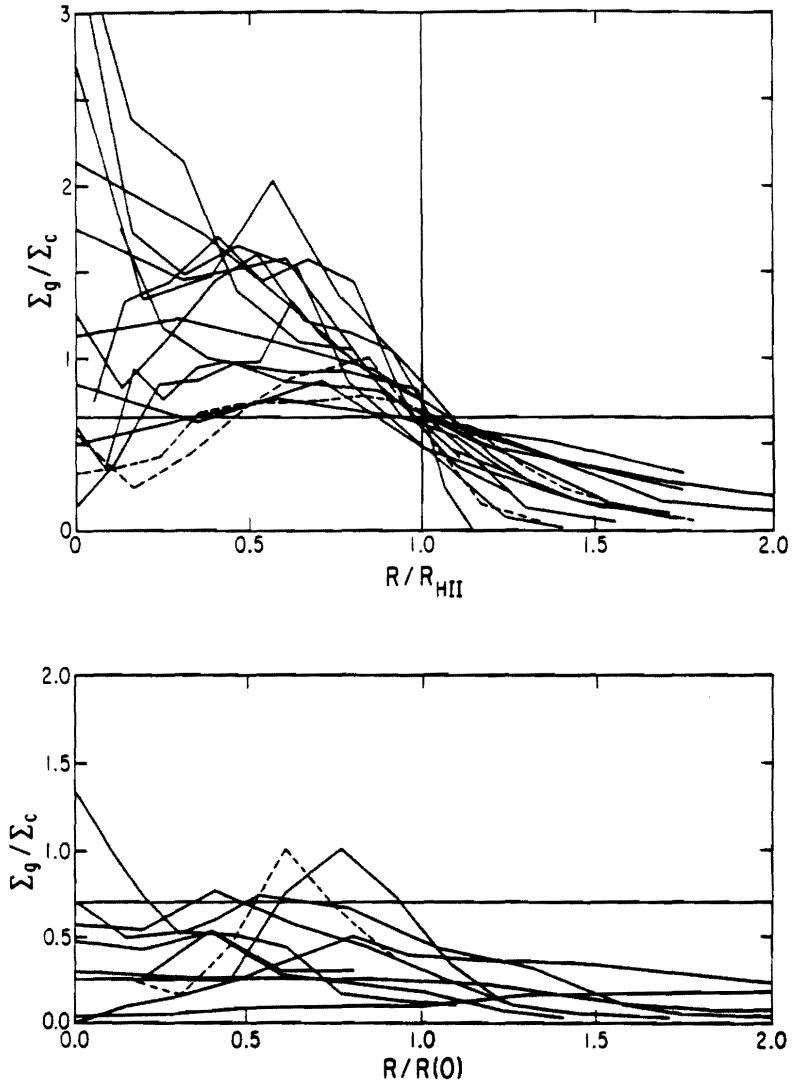

Figure 7. Variation of disk stability criterion $1/Q$ with radius for active star forming spirals (top) and low-SFR spirals (bottom). From Kennicutt (1989)

huge gas masses but negligible SFRs, are among the most enigmatic galaxies in the conventional Schmidt law picture. For example the prototype LSB, Malin 1, possesses a 200 kpc H I disk with a mass of $\sim 2 \times 10^{11} M_{\odot}$ ($H_0 = 75$), but with little detectable star formation (Impey & Bothun 1989). In the threshold picture the low SFRs are readily explained if the gas disk

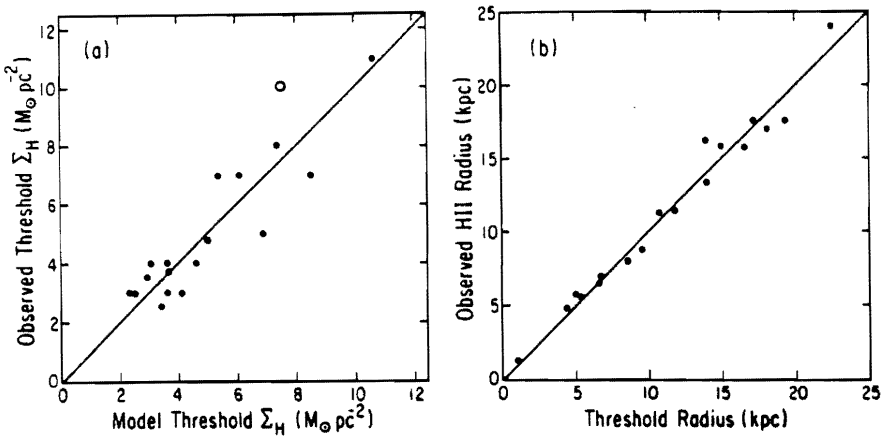

Figure 8. Comparison of predicted and observed threshold densities (left) and radii (right) for galaxies in the top panel of Fig. 7.

is sufficiently extended that $Q > 1.5$ everywhere. The nearly face-on orientation of Malin 1 makes it difficult to derive an accurate rotation curve (and hence Σ_c), but Impey & Bothun (1989) showed that its typical disk surface density is subcritical according to the Q criterion used here. Similar analyses of gas-rich S0 galaxies by Kennicutt (1989) and Eder (1990) reached the same conclusion.

The most comprehensive analysis of LSBs has been published recently by van der Hulst *et al.* (1993). These authors obtained VLA H I maps for 6 LSBs, and compared the radial variation in gas density with $\Sigma_c(r)$, following Kennicutt (1989). The resulting comparison is reproduced in Figure 9. In most of the galaxies $\Sigma(HI)$ indeed lies just below the $Q \sim 1.5$ threshold. In a few instances the H I density meets or exceeds the threshold value over a limited radial range, and in these cases the regions coincide with locations of H II regions. This conclusion could be modified if the galaxies contain substantial masses in molecular gas, but the absence of detected CO emission in most LSBs makes this unlikely.

Taylor *et al.* (1994) have used VLA H I maps and optical imaging of 5 H II galaxies to compare the spatial extents of the star formation with that expected from a threshold model. The rotation curves in these low-mass irregular and spiral galaxies generally show solid-body rotation over most of the optical disk, which yields a constant value of the critical density if the Toomre criterion is applied. However the galaxies show large spatial variations in H I density, so one can test for the presence of a threshold effect. Thresholds are seen in all cases, at densities roughly corresponding to those predicted by the Q model. However the range in critical densities cluster

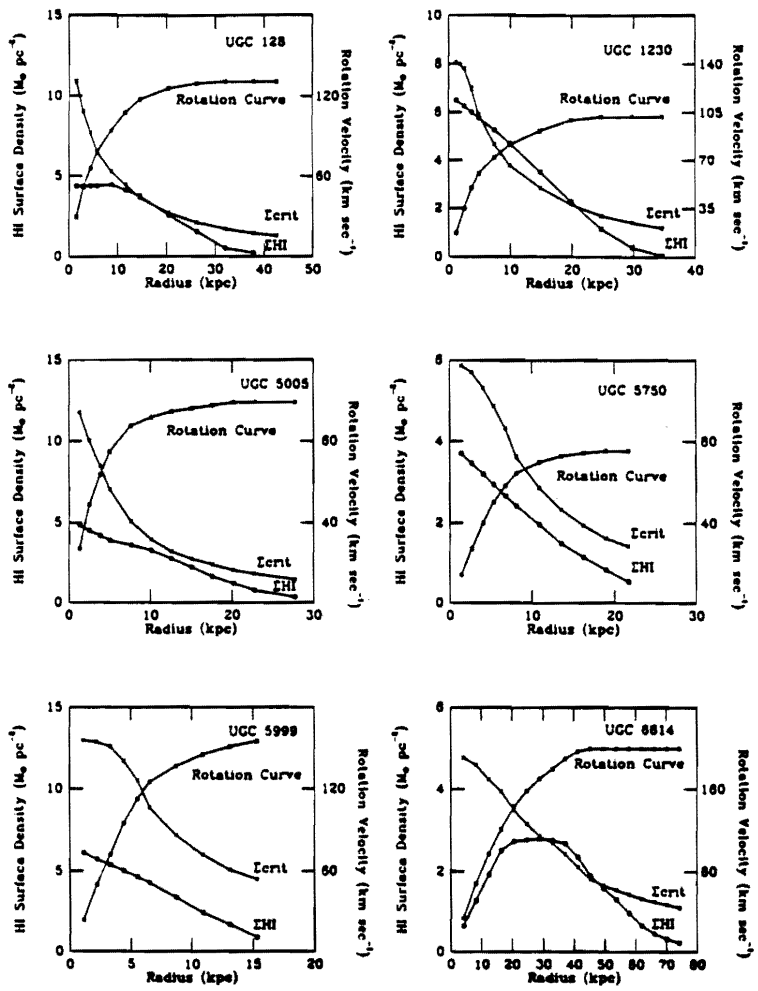

Figure 9. Rotation curves, HI density distributions, and critical density distributions for 6 low surface brightness galaxies, from van der Hulst *et al.* (1993).

around a common value near 10^{21} H cm^{-2}, so other threshold mechanisms cannot be ruled out. Similar values for the threshold column densities were observed in a sample of nearby dwarf irregular galaxies by Skillman (1987), and Chamandaris *et al.* (1993) identified a threshold in the ring galaxy Arp 10. Kennicutt *et al.* (1995) have used Hα CCD images and H I maps of the Magellanic Clouds to perform the same test. They identify threshold densities of $\sim$0.7 and 2.0 $\times 10^{20}$ H cm^{21} for the LMC and SMC, respectively, compared to predicted values of $\sim$1.0–1.3 $\times 10^{21}$. It is not clear whether

this disagreement indicates a breakdown in the Q model for these galaxies or is due to different gas velocity dispersions or some other factor. Overall it appears that the star formation properties of the irregular galaxies are in qualitative accord with the model, but the level of quantitative agreement may not be as good as for more massive spirals.

An especially powerful test for dynamically-induced threshold effects would be to identify galaxies with *azimuthal* variations in column density which cross the $Q = 1.5$ threshold, and test whether the SFR varies nonlinearly across this transition. Grand-design spirals offer an especially attractive laboratory for such tests, but until recently CO and H I data with sufficient spatial resolution were not available. Rand (1993) has used interferometer CO and H I maps of M51 to perform this test. He measured the variation in gas density and SFR (via Hα) across the spiral arms in M51, and compared the gas densities in the arm and interarm regions with the threshold densities expected from the Q criterion, taking into account the effects of the spiral density wave on the epicyclic frequency κ. He found that the gas surface densities in the arm and interarm regions bracketed the expected threshold value from the Q criterion, which is consistent with the strong arm/interarm contrast in Hα relative to CO. Uncertainties in several parameters, not the least the CO–H_2 conversion factor, may influence these conclusions, but Rand's analysis demonstrates the value of this approach, and it should be extended to other galaxies.

Despite these successes, the Q model is flatly contradicted by one class of galaxies— low-mass spirals. Two galaxies of this type, M33 and NGC 2403, are indicated by the dashed lines in Figure 7. Both exhibit subcritical surface densities over much of their inner disks, even though vigorous star formation is taking place in these regions. Another nearby spiral, NGC 300, appears to show similar behavior (Ferguson, this meeting). These spirals differ from their more massive counterparts in two significant respects; they have lower disk metal abundances, which might affect the CO/H_2 conversion ratio, and they exhibit slowly rising rotation curves over most of the inner disks. The former effect might lead to an underestimate of the gas densities in the inner disks, and explain the apparently subcritical densities in the active star forming regions. The latter effect might lead to a breakdown of the Toomre criterion for predicting the critical densities for cloud formation and star formation, as discussed below.

Another approach to testing the consequences of the star formation thresholds is to explore their effects on the star formation histories and chemical evolution of disks. An early exploration of this kind was made by Lacy & Fall (1985), who modelled the chemical evolution of the Galactic disk using a Schmidt law with a Q threshold. The most extensive analysis of this kind has been published by Wang & Silk (1994), who model the tem-

poral evolution of the SFR and chemical enrichment in the Galactic disk using a complete star formation model which incorporates a Q threshold and self-regulation. Their model is successful at reproducing the observed SFR, the G-dwarf metallicity distribution, the local age-metallicity relation, and radial variations in gas density, SFR, and abudances. Chamcham *et al.* (1993) have constructed a similar model, but argue that gas flows and/or infall are needed to reproduce the abundance properties of the Galactic disk, an old problem with the conventional Schmidt law models. Firmani *et al.* (1994) follow the viscous evolution of disks incorporating a Q star formation parameter, and are able to produce exponential disks, flat rotation curves, and realistic Schmidt star formation laws. In different kind of application, the evolution of a starburst triggered by a high Q threshold has been discussed by Firmani & Tutukov (1993) and Elmegreen (1994a).

3.4. PHYSICAL NATURE OF THE THRESHOLDS

Although we refer to the observed cutoffs in star formation as "star formation thresholds," the underlying physical mechanism almost certainly involves regulation of some other process leading to star formation, such as the formation of gravitationally bound cloud complexes, the formation of molecular clouds, density wave triggering of cloud growth, or some other process. In this section we briefly discuss possible threshold mechanisms and alternatives which have been proposed to the Toomre Q criterion.

3.4.1. *Shear and Tidal Instabilities*

The physical motivation for applying the Safranov/Toomre criterion in Kennicutt (1989) was the idea that the onset of large-scale star formation might be dictated primarily by the growth of gravitational perturbations leading to cloud formation. However the Toomre criterion— which governs long-wavelength disk instabilities— may not describe these cloud growth instabilities in all conditions. Elmegreen (1993b) proposed an alternative critical density condition in which the epicyclic frequency κ is replaced with the shear rate, which in terms of the Oort constants is 2.5 A (*vs* $\kappa^2 = [4B(B-A)]$). Kenney *et al.* (1993) proposed a tidal criterion, in which κ^2 is replaced by $[3A(A-B)]$. Both of these critical densities converge to the Toomre value in the limit of constant rotation velocity (with a small scaling factor), but tend toward zero in the limit of solid body rotation (*vs* a constant critical density for the Q criterion). Hence the Elmegreen and Kenney *et al.* criteria predict much lower thresholds in the central parts of galaxies, or in low-mass spiral and irregular galaxies where there is relatively little shear. This could explain the high SFRs in spirals like M33, NGC 2403, or NGC 300, where there is an apparent failure of the Q model.

However it does not explain the observation of star formation thresholds in Magellanic irregular galaxies (Skillman 1987, Taylor *et al.* 1994), which are accounted for quite readily by the Q model. Perhaps the best way to distinguish between these respective models is to measure the SFRs and gas densities near the centers of massive spiral galaxies, where the Q model predicts a much higher threshold density in most cases.

3.4.2. *Two-Fluid and Combined Instabilities*
The simple Toomre criterion applied by Kennicutt (1989) and others applies strictly to a purely gaseous disk, and it is well known that the interaction between the stellar and gaseous disks can act to destabilize the gas disk (Jog & Solomon 1984). The consequences of adopting a more realistic two-fluid stability condition have been explored by Jog (1992), Elmegreen (1994b), Gammie (1994), and Fuchs (this meeting). While the threshold conditions predicted by these models are in qualitative accord with the simpler Toomre condition, Elmegreen (1994b) concludes that the differences in predicted threshold radii and densities should be measurable. The paucity of data on the velocity dispersions of the stellar *and* gas disks of nearby galaxies hampers such a test at present. Elmegreen (1991) and Gammie (1994) also consider a wide range of combined instability mechanisms for galactic gas layers, including gravitational, shear, magnetic Rayleigh-Taylor, and thermal instabilities. The interplay between these different instabilities may regulate star formation so that $Q \sim 1$ (Elmegreen 1991).

3.4.3. *Spiral Density Wave Thresholds*
If spiral density waves are the primary triggering agent for large-scale star formation, they could produce threshold features as well (Wyse 1986, Wyse & Silk 1987). These authors have proposed a modified Schmidt law of form:

$$R = A\Sigma^n(\Omega - \Omega_p)$$

where Ω and Ω_p are the disk and spiral pattern angular frequencies. Such a model will produce a cutoff in star formation at the corotation radius, and a roughly $1/r$ term from $\Omega - \Omega_p$ inside this radius. Kennicutt (1989) has argued that the range of star formation properties in grand-design and flocculent spirals suggests a decoupling between the stellar disk instabilities (which lead to spiral density waves) and the gas instabilities (which lead to large-scale star formation), but this conjecture has not been tested observationally.

3.4.4. *Molecular vs Gravitational Thresholds*
The close association of star formation with molecular cloud complexes implies that the formation of gravitationally bound clouds in itself is not a

sufficient condition for large-scale star formation, and it raises the question of whether it is the formation of molecular gas, rather than the formation of gravitationally bound clouds, that is the crucial regulator of star formation. Are the formation of bound clouds and molecular clouds manifestations of the same threshold process, or are gravitational and molecular formation thresholds distinct processes which are decoupled from each other (and from star formation) in some environments?

An insightful exploration of the interplay between the formation of gravitational bound clouds and molecular clouds has been published by Elmegreen (1993a). In the solar neighborhood the formation of gravitationally bound clouds and molecular clouds are closely associated, because the threshold column densities for forming both objects are nearly the same. However the dependence of these thresholds on the interstellar pressure and metallicity are quite different, so in other environments the formation of bound clouds and molecular gas may be decoupled.

These ideas have interesting implications for the interpretation of the observed star formation thresholds in different types of galaxies. For example in disks with conditions similar to those found in the solar neighborhood, the critical densities for bound cloud formation and molecule formation are similar, and hence the observed star formation thresholds probably coincide with the threshold which separates gravitationally bound *and* molecular clouds from diffuse (pressure-supported) atomic gas. However these conditions do not hold in low-mass irregular galaxies, where low ISM pressures and low metallicities lead to threshold densities for molecular cloud formation which are much higher than the corresponding threshold for the formation of gravitationally bound clouds. In those environments gravitational instabilities will produce bound *atomic* cloud complexes, which later form molecular cores and stars within the larger atomic clouds (Elmegreen 1993a). At the other extreme, in metal-rich and/or high pressure interstellar environments, such as that found in the inner Galaxy or in massive gas-rich spirals such as M51, conditions will favor the formation of molecular gas at column densities which are too low to form gravitationally bound clouds. In these galaxies we would expect the observed star formation thresholds to occur in a largely molecular medium, consisting of bound molecular clouds within a substrate of diffuse molecular and atomic gas. In such galaxies it is the gravitational threshold, not the molecular formation (self-shielding) threshold, which is critical for initiating large-scale star formation. However in low-metallicity or low-pressure environments, such as in dwarf galaxies or the outer disks of spirals, gravitational stabilities may be secondary to molecule formation in leading to efficient large-scale star formation (*cf.* Lin & Murray 1992).

There is some observational evidence to support this basic picture. CO

observations of the inner Galaxy reveal a diffuse molecular medium surrounding the molecular clouds (e.g., Polk *et al.* 1988, Stark *et al.* 1991), and the center of the nuclear starburst galaxy NGC 1808 shows evidence for a similar medium (Aalto *et al.* 1994). Observations of the CO and cold H I in the Magellanic Clouds (e.g., Israel *et al.* 1993; Dickey *et al.* 1994) are consistent with the cloud structure described by Elmegreen (1993a), though the interpretation of these data is complicated by possible changes in the CO/H_2 coupling in these metal-poor environments. It should be possible to separate these gravitational and molecular thresholds by obtaining sensitive maps of the CO, H I and Hα in nearby galaxies which span a broad range of interstellar pressures, metal abundances, and rotation curves.

4. Regulation of the SFR

At high gas densities most galaxies show remarkably similar star formation laws, roughly following a Schmidt law with index $N \sim 1.3$–1.5, and constant zeropoint (see Figure 6 and Kennicutt 1989). This strongly hints toward some sort of regulation of the SFR, either from the gas–star conversion process itself, or from a self-regulating interaction of the star formation and the ISM. In this section I discuss some of the current ideas on the underlying physics of the star formation law in this high-density regime.

4.1. ISM-STAR INTERACTIONS

If one adopts as a working hypothesis that the SFR is determined purely by the efficiency and time scale for converting gas to stars, then one can identify several relevant processes that might produce a Schmidt law similar to what is observed. A thorough discussion of this subject is given by Larson (1987). For example, a linear Schmidt law can be obtained simply by postulating that the SFR is regulated by a constant star formation efficiency. Combining the local efficiency of ~5% in interstellar clouds with a typical dynamical time scale of 10^8 years for disks yields a mean SFR per unit gas density which is very close to the mean global value observed in nearby spirals (e.g., Figure 2). A more nonlinear Schmidt law (e.g., $N \sim 2$) would result if the time scale for forming clouds τ in an ISM with surface density Σ scales with Σ^{-1}. Then the SFR per unit area will scale as $\Sigma_g/\tau \propto \Sigma_g^2$ (Larson 1987). Unfortunately the scale-free nature of the Schmidt power law makes it difficult to identify observationally a single underlying physical mechanism. However as discussed by Larson (1987), there are several processes, including gravitational instabilities, density-wave compression, accretion in a shear flow, and cloud coagulation, which have roughly the time scales and density dependence needed to explain qualitatively the form of the observed Schmidt law.

4.2. STAR-ISM INTERACTIONS AND FEEDBACK

An alternative possibility is that the SFR above the threshold is not determined uniquely by the gas density, but rather by a self-limiting feedback process between the ISM and the SFR itself. Self-regulated star formation models have been popular for some time. Proposed regulation mechanisms have included disk Ly-α opacity (Cox 1983) and energy injection from stellar winds and/or supernovae (e.g., Franco & Cox 1983; Dopita 1985, 1990; Parravano 1989; Burkert *et al.* 1992; Firmani & Tutukov 1992, 1994; Wang & Silk 1994; Dopita & Ryder 1994; Köppen *et al.* 1994). The combined effects of self-regulation and Q thresholds have been explored by Wang & Silk (1994) and Firmani & Tutukov (1994). A thorough review of the subject has been published recently by Shore & Ferrini (1994), and I will only highlight a few examples that are especially relevant to interpreting the large-scale star formation law.

Although the details of the self-regulation mechanisms vary between different models, in most cases the limiting SFR is determined by the balance between the turbulent ISM pressure or heating introduced from stellar winds and supernovae and the ambient thermal or binding pressure of the warm ISM. If the input from star formation is much below the equilibrium pressure the gas disk contracts, promoting cloud growth and a higher SFR. If the SFR exceeds its equilibrium value the excess energy input will disperse clouds or even the disk itself, cutting off star formation until an equilibrium condition is achieved again. This process often leads to a Schmidt-like SFR–density law, with N typically ranging from 1.3–2 (e.g., Parravano 1989; Dopita 1990; Köppen *et al.* 1994; Friedli & Benz 1995). Because the binding pressure of the ISM also scales with the stellar surface density, some models predict a compound Schmidt law of the form:

$$\Sigma_{sf} \propto \Sigma_g^N \, \Sigma_*^M$$

where Σ_g and Σ_* are the gas and stellar surface densities, respectively (e.g., Dopita 1985, 1990).

Many of these models contain too many physical variables and free parameters to offer a robust observational test, but some predict an explicit form for the star formation law which can be compared to observations. For example, the models of Dopita (1985, 1990) predict compound Schmidt laws of the form given above, with $N = 1$–1.33 and $M \sim 1$. Dopita & Ryder (1994) also consider a law of the form $\Sigma_{sf} \propto \Sigma_g \Omega$, where Ω is the angular rotation speed.

Observational evidence for these types of law is presented by Ryder (1993), who finds that the ratio of the SFR to H I surface density is correlated with local *stellar* surface density. When the latter is parametrized in

terms of I-band surface brightness they find a best fit to a law:

$$SFR \propto \Sigma_{HI}^{0.9}\ \Sigma_I^{0.64}$$

similar to that predicted by their self-regulating models. Kennicutt & Martin (1995) have independently tested for a compound Schmidt law for the galaxy sample shown in Figure 2, by correlating the mean Hα surface brightness with the product of the mean gas density (H I + H_2) and the stellar (V) surface brightness. We do find an excellent correlation with slope near unity, as predicted by the pressure-regulated model (e.g., Dopita 1985), but the fit is no better than a simple Schmidt law with $N > 1$. A problem we encountered with the interpretation of both of these results is that the stellar surface brightness in most disks is strongly correlated with the surface density of molecular gas— CO disks are exponential with roughly the same scale length as the stars— so it is difficult to determine *a priori* whether a correlation of SFR with stellar density is actually due to a dependence on Σ_* independent of Σ_g or simply a dependence on Σ_g to a higher power. This could be tested in principle by analyzing a sample of galaxies with similar stellar disk properties but a wide range of gas disks or *vice versa*. Unfortunately the range of stellar disk properties in most available samples is too limited for this purpose, and the tendency of gas disks to follow a $Q \sim 1$ profile forces a coupling between the stellar and gaseous disk profiles (Kennicutt 1989), which also limits the range of disk properties which can be readily observed.

Perhaps the most impressive demonstration of the importance of stellar wind and supernova feedback for the SFR and disk evolution comes from numerical simulations. When the formation of disk galaxies is simulated using particle/gas models which include the effects of self-gravity, gas cooling, and star formation, but without mechanical feedback from star formation, the resulting disks are too condensed, and star formation tends to proceed more rapidly than is observed (Navarro & Benz 1991). More recent models which incorporate explicitly the effects of stellar feedback show that the global SFR is a very sensitive to the mechanical energy injection rate (Navarro & White 1994; Friedli & Benz 1995). This is illustrated in Figure 10, which shows the dependence of the equilibrium SFR on the supernova rate and mechanical energy injection rates, for a set of disk simulations from from Friedli & Benz (1995). Similar results have been derived by Navarro & White (1994). The models also demonstrate that the feedback affects the spatial distribution of the star formation; for example the spatial concentration of the star formation in spiral arms can be wiped out if the feedback efficiency is too high. Many of the simulations bear a striking resemblance to real galaxies, and some are capable of reproducing the observed star formation law (Friedli & Benz 1995).

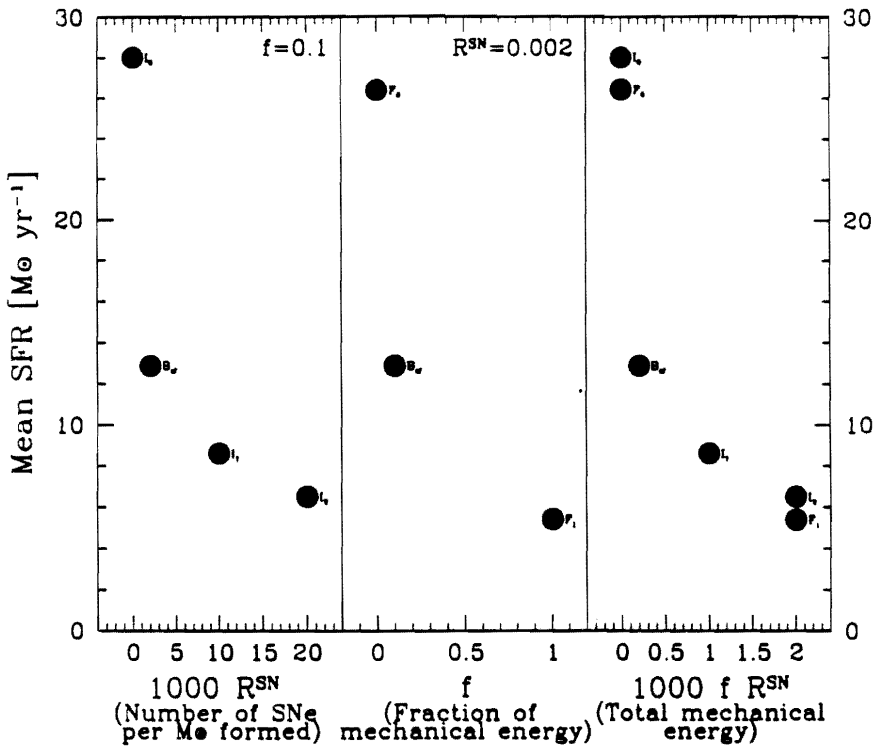

Figure 10. **Dependence of the SFR per unit gas mass on the mechanical energy injection rate from massive stars and supernovae, from models of Friedli & Bens (1995).**

The critical parameter in these models is the ratio of *mechanical* energy imparted to the ISM from a generation of stars to the initial mass of stars formed, the "feedback efficiency" referred to above. The *total* energy input from stars and supernovae can be calculated in principle using stellar models (e.g., Leitherer & Heckman 1995), but the results are sensitive to metallicity and the temporal properties of the star formation event, and are sensitive to uncertainties in the stellar evolution models themselves. A further uncertainty is the fraction of the stellar wind and supernova energy which is transferred into bulk kinetic energy in the ISM (thermal energy imparted to the ISM is quickly radiated away and does not influence the SFR). This quantity is not easily calculated and may well depend on the clustering properties of the star formation (e.g., Mac Low & McCray 1989; Norman & Ikeuchi 1989; Heiles 1990). Observations of the kinematics of the ISM in star forming regions may provide more direct measurements of these energy injection parameters and their variation in different environments (e.g., Chu & Kennicutt 1994). Despite these uncertainties the simulations

clearly demonstrate the importance of the feedback from star formation on the formation, evolution, and structure of disk galaxies.

As impressive as these state-of-the-art 2D simulations are, computational limitations restrict the range of parameter space which can be explored. In particular, relatively simple "recipes" must be adopted for the SFR as a function of gas density, the growth rates of clouds and star formation, and the transfer of energy from stars back to the ISM. The effects of varying these underlying assumptions have been explored in a series of papers by Struck-Marcell & Scalo (1987) and references therein. Their single-zone "Oort models" lack the sophistication of the modern 2D simulations, but this approach has allowed them to adopt more realistic algorithms for cloud formation and destruction, star formation, and the nonlinear growth of coherent structures and starbursts from delayed feedback effects.

One of the most significant results of this work was the discovery that the nature of the star–ISM feedback and the resulting temporal evolution of the system depends critically on the time delays between cloud formation, star formation, and the subsequent disruption of the surrounding ISM by winds and supernovae. For instantanous models (i.e., short delay time for feedback) the systems exhibit negative feedback, similar to the behavior exhibited in the 2D models described above (e.g., Fig. 10); local perturbations to the SFR tend to be damped out. However as the delay time between cloud formation and stellar energy injection becomes comparable to the growth time for forming clouds, the systems become unstable and the models display positive feedback, first exhibiting a limit cycle behavior, then a chaotic series of bursts punctuated by quiescent periods as the feedback delays are increased further. Bursts can also be introduced in other ways, for example by introducing gas into the system as a function of time (Vázquez & Scalo 1989). Hence the negative feedback behavior seen in the 2D models occurs over only a limited set of conditions, and for many realistic parameters the qualitative character of the star-ISM interaction is radically different, with much of the star formation occuring in massive bursts. It is possible that some of the limit-cycle behavior exhibited in these models is an artifact of the single-zone boundary conditions (Scalo, private communication), but the qualitative results provide a reminder that more sophisticated 2D multi-particle models need to be performed over a wider range of input conditions and "recipes."

Taken together these simulations suggest that the effects of star formation on the ISM may be as important as the SFR–gas density law in driving the global star formation and evolution of galaxies. At present this subject is being driven by theory and simulations, in much the same way that the entire subject of star formation in galaxies was being driven by theory 20 years ago. Although the inherent complexity of star–ISM interactions on

galactic scales is a formidable obstacle to observers, the potential for new physical insights into the regulation of the SFR and galaxy evolution make this an exciting and potentially rewarding field for future investigation.

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