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The Schmidt Law: Is it Universal and What are its Implications?

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Abstract. Galaxies exhibit an immense diversity in their star formation properties, yet these properties appear to be linked by a few underlying scaling laws. One of the most fundamental of these laws is the star formation law relating the surface densities of star formation and cold gas in galaxies. Virtually the entire range of global star formation rates in galaxies can be reproduced by the simple combination of a Schmidt power law relation at high density with a sharp turnover in star formation rate below a threshold surface density. Thanks to a new generation of multi-wavelength observations of nearby galaxies, it is now possible to test the validity of this description as a function of physical scale and interstellar environment. These new observations also offer new clues to the physical processes that underlie and drive the observed star formation law. This paper reviews recent progress in our observational and theoretical understanding of the star formation law in the Schmidt power law and threshold regimes.

1. Introduction

Despite the many recent advances in our observations and theoretical understanding of star formation on the local scale, our understanding of star formation on galactic scales is at a relatively embryonic stage. A deeper understanding is crucial for a complete theory of star formation itself, because many of the agents that trigger cloud formation and regulate the star formation rate (SFR) appear to operate on the scales of hundreds of parsecs or larger. Such an understanding is also a necessary prerequisite for a complete theory of galaxy formation and evolution; indeed our poor understanding of star formation and the associated feedback processes between young stars and the interstellar medium stand as the primary impediments to galaxy formation and evolution models today. This is hardly surprising. The physical process involved are complex and challenge the best of our theorists and numerical simulators.

Despite this imposing challenge, nature has kindly provided us with tantalizing empirical hints to these processes, in the form of a suite of remarkably tight scaling laws relating the large-scale SFR to the large-scale properties of the interstellar gas. The most well-known of these is the Schmidt law relating the SFR surface densities to the total gas surface density (e.g., Schmidt 1963, Kennicutt 1998b). More recently a similar, linear scaling relation has been discovered between the total SFR and the mass of dense molecular gas (e.g., Gao & Solomon 2004). These relations hold over large ranges of densities, host galaxy properties, and star formation environments, and when combined with low-density threshold effects provide a nearly complete empirical prescription for the large-scale SFR.

In this paper I begin by reviewing the observations of the star formation law in nearby galaxies, and some of the outstanding questions that remain to be addressed by observation and theory. I then present some recent results from the *Spitzer* Infrared Nearby Galaxies Survey (SINGS) on the spatially-resolved Schmidt law in galaxies.

2. Basic Observations and Unanswered Questions

Schmidt (1959) originally formulated the star formation law as a power-law relation between the volume densities of star formation and gas, but since volume densities are not readily measurable most current applications relate the projected surface densities of these quantities:

$$\Sigma_{SFR} = A \; \Sigma^{N}{}_{gas} \tag{1}$$

For the sake of convenience whenever I refer to “density” in this paper I always mean the surface density. For most applications the gas density Σ_{gas} refers to the total surface density of cold hydrogen (atomic and molecular), but it is important of course to test the form of the relation for different gas components, as will be discussed later.

Since the publication of Schmidt’s original papers there have been dozens of empirical studies correlating the surface densities of various star formation tracers with the surface densities of HI, molecular gas, or both (see Kennicutt 1997, 1998b for a review of papers up to that time). A breakthrough occurred about 10 years ago, when sufficient data on extinction-corrected SFRs, CO maps, and HI maps became available to measure the correlation over a large dynamic range in surface densities. The results are summarized in Figure 1, which is adapted from Kennicutt (1998b). The left panel plots the disk-averaged SFRs and gas surface densities for normal spirals (solid circles), infrared-luminous starbursts (squares), and the central regions of normal galaxies (open circles). The best fitting relation has a slope $N = 1.4 \pm 0.1$. We return to the righthand panel later.

Although the Schmidt power law seems to provide an excellent description of the SFR at high gas surface densities, at low densities one often observes a rapid transition or threshold, below which the SFR declines more rapidly. These thresholds are most readily observed as radial truncations to disks observed in Hα; star formation often persists beyond this threshold radius but at a much lower rate (e.g., Kennicutt 1989, Martin & Kennicutt 2001). In some gas-poor galaxies this threshold regime extends across the entire radius of the disk (e.g., Kennicutt 1989, van der Hulst et al. 1993). It is the combination of a relatively mild-slope power-law behavior at high density with a steeper, nonlinear behavior at low density that can account for the enormous range in SFRs and SFR densities among galaxies.

This nonlinear dependence on total gas surface density is not the only scaling law of its kind. In a series of papers Gao & Solomon (2004) have correlated the infrared luminosities of actively star-forming galaxies with the total masses

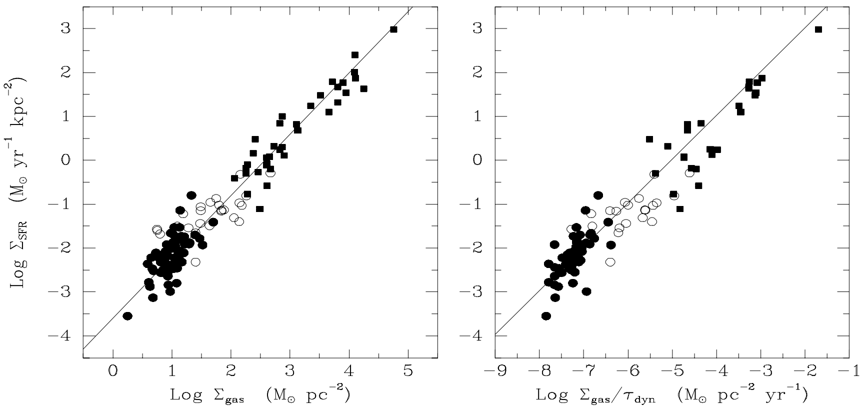

Figure 1. *Left:* The global Schmidt law in galaxies parametrized in terms of the SFR surface density and the total (atomic plus molecular) gas surface density. *Right:* The same data fitted to a "Silk law", where the SFR surface density is plotted against the ratio of gas surface density to mean disk orbit time. Both figures adapted from Kennicutt (1998), copyright AAS.

of dense molecular gas as traced primarily in the HCN line. This reveals comparably tight but linear ($N = 1$) relation, again observed over a wide range of SFRs. The HCN is thought to trace the mass of dense stellar cores in star-forming regions, and hence this result suggests that the fraction of core mass that is ultimately converted to stars is relatively insensitive to the scale and environment in which the star formation takes place.

Beyond this rudimentary picture a plethora of questions remain unanswered. Are these strong correlations universal, or are they partly the result of selection effects in the datasets assembled to date? Is part of the scatter observed in the relations physical, and if so are the residuals systematically correlated with other properties of the galaxies? Does the disk-integrated Schmidt law also describe the local relationship between SFR and gas densities *within* galaxies, and if so on what linear scale does this law break down. Is the Schmidt law a causal physical relationship, or is it merely the empirical consequence of a deeper underlying correlation? For example, the righthand panel of Figure 1 shows the same SFR densities plotted not as a function of gas surface density but rather the ratio of the gas density to the local dynamical (disk orbit) time, following a relation proposed by Silk (1997) and others. The latter correlation is nearly as tight as the Schmidt law, so which (if either) is the fundamental correlation, and which is merely the empirical consequence of the other? Likewise, is the observed correlation of the SFR with the total surface density of gas fundamental, or is it the result of a stronger correlation with the molecular or atomic gas surface densities by themselves. And of course an overarching unanswered question is the underlying physical origin of the scaling law.

A similar set of questions surround the apparent star formation thresholds that are observed in many galaxies. Are the strong radial transitions observed in the HII region disks also seen in other star formation tracers? What is the relationship between the SFR density and gas density in the subcritical regime;

is it determined by a different Schmidt-type law, or does the relationship between SFR and gas surface densities become more stochastic in this regime? And again, what is the physical origin of the observed thresholds? Is it largely dictated by gravitational stability processes, ISM phase transitions, magneto-gravitational instabilities, or more complicated processes? In the remainder of this paper I review some recent observations directed at answering some of these questions, with emphasis on some new results from my collaborators.

3. The Disk-Averaged Star Formation Law

The global star formation laws shown in Figure 1 show a considerable dispersion (approximately ±0.4 dex rms), and it is not clear how much of this dispersion is physical, rather than reflecting observational uncertainties in the measured SFRs and gas densities. For the Kennicutt (1998b) study the largest observational errors were in the extinction corrections applied to the Hα-based SFRs (usually a constant correction factor of 1.1 mag), and uncertainties arising from the application of a constant CO/H_2 conversion factor (X-factor) to compute molecular surface densities. Recently I initiated a project to enlarge and improve on the Kennicutt (1998b) dataset. Spatially-resolved SFR, CO, and HI data are now available for more than twice as many galaxies as a decade ago, and for most of these we can apply individual Hα extinction corrections, either from optical spectroscopic measurements or Pa$\,\alpha$ line imaging at 1.87$\,\mu$m, which is nearly free of dust extinction. In addition we have applied individual corrections to the Hα fluxes for [NII] forbidden line contamination, and have used Hα or infrared maps of the galaxies to precisely measure the size of the star-forming region over which the SFR and gas surface densities are averaged (in the 1998 study we used the RC3 diameters to approximate these radii).

This work is still in progress, but a preliminary plot of the intermediate results is shown in Figure 2. The new data (solid points) confirm the relation found by Kennicutt (1998), with an $N = 1.4$ Schmidt law providing a good fit to the new data. Interestingly, although there are fewer disprepant points that found in the Kennicutt (1998) analysis (mainly because of the improved extinction and [NII] corrections and better disk diameters), the overall dispersion of the Schmidt law is similar to that seen earlier. This suggests that the observed dispersion is either real, or that other systematic effects (e.g., a variable CO/H_2 X-factor) are responsible for most of the dispersion.

For the first time we have enough data to isolate a possible second parameter influencing the relation, metallicity. The solid points in Figure 2 correspond to luminous spiral and irregular galaxies with $M_B < -17$, while fainter dwarf irregular galaxies are shown as open circles. S-Irr galaxies follow a metallicity-luminosity relation, and this transition luminosity correponds to a metallicity of $Z \sim 0.2 - 0.3 Z_\odot$ (Skillman et al. 1989). The galaxies with low SFR intensities generally follow the main Schmidt law, but the most active star-forming low-metallicity galaxies tend to lie well above (or to the left) of the main law defined by the more luminous galaxies.

One interpretation of this difference is that the gas surface densities in the starbursting dwarf galaxies are systematically underestimated, due to a breakdown in the CO/H_2 X-factor. Indeed in many of these galaxies CO is either

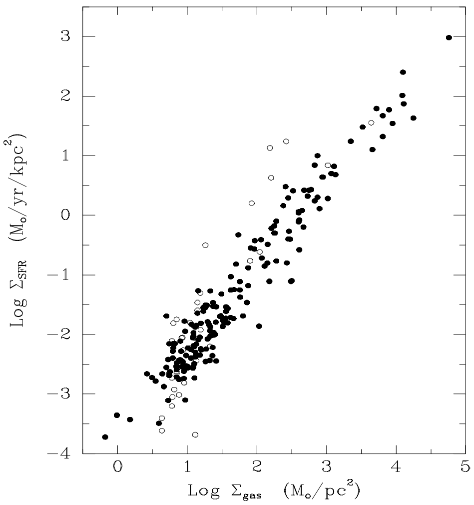

Figure 2. Disk-averaged SFR surface density vs gas density relation for normal and starburst galaxies, from a new study in progress. Solid point denote luminous spiral and irregular galaxies with $M_B < -17$, while fainter dwarf irregular galaxies are shown as open circles. This corresponds to a transition in gas-phase metallicity at about 0.2–0.3 $Z_\odot$. The solid line shows a slope $N = 1.4$ for reference (not a fit to the data).

undetected or very weak, despite the intense star formation bursts, and the authors of these papers often suggest that CO underestimates the true molecular gas content. However other explanations are possible. The most intense starbursts could be observed at an evolved stage where UV radiation has dissociated and dispersed much of the gas, or the Schmidt law in these systems could be much steeper than in normal galaxies. I am hoping that we will be able to distinguish between these alternatives when all of the data are analyzed, but in any case we can identify at least one systematic source of scatter in the Schmidt law, at least when a constant X factor is assumed.

4. The Spatially-Resolved Schmidt Law in Galaxies

One of the limitations of disk-averaged studies of the star formation law is that many parameters apart from gas density and SFR vary systematically between galaxies, so isolating underlying physical mechanisms for the observed star formation laws can be problematic. Moreover the disk-integrated measurements average out enormous local variations in the gas and SFR surface densities within disks, and may well mask important behaviors that are only manifested on a local scale. Fortunately the rapid advances in multi-wavelength observations of nearby galaxies now make it possible to study the behavior of the star formation law on a spatially-resolved basis within galaxies, either as a function of radius (azimuthally averaged) in disks or on a point by point basis.

Until recently the most comprehensive spatially-resolved studies of galaxies were studies of radially-averaged SFR and gas density profiles by Kennicutt

(1989) and Martin & Kennicutt (2001). These were based on Hα measurements, usually with a constant factor applied to correct for extinction, a precarious practice at best. These data did provide quantitative measurements of the radial star formation thresholds, and revealed a Schmidt law at high surface density that was consistent with the disk-averaged law ($N \sim 1.3 - 1.4$), but with large systematic uncertainties because of extinction. The problem has been revisited by Wong & Blitz (2002), Boissier et al. (2003), Komugi et al. (2005), and Schuster et al. (2006) using radial profiles of galaxies, and by Kuno et al. (1995), Zhang et al. (2001) and Heyer et al. (2004) using point-by-point measurements. Most of these studies yield reasonable fits to a Schmiddt power law with slope $N \sim 1.5 \pm 0.3$. A few studies derive much shallower or steeper laws (e.g., Kuno et al. 1995, Boisier et al. 2003), but in all of those cases the authors applied values of the CO/H_2 (X) conversion factor that were either very different from the normally applied value or they used a variable X-factor. This underscores the sensitivity of the derived star formation law on the methods used to convert measured CO line intensities to molecular hydrogen surface densities.

The other major challenge in carrying out such studies is the need to accurately correct for extinction in determining the local SFR surface densities. Most of the studies above used constant extinction corrections, which clearly is a poor approximation at best. The problem is especially vexing for applications to the Schmidt law, because one would naively expect the column density of dust– or the amount of extinction expressed in magnitudes– to correlate roughly linearly with the column density or surface density of gas. The effect of this bias depends on the surface density regime of interest. If we assume approximately the same ratio of extinction to column density as observed in the galaxy the absence of an extinction correction would cause the Schmidt index N to be underestimated by as much as 1 for high column densities ($N_H > 10^{22}\,\mathrm{cm}^{-2}$ or $\Sigma_H > 100 M_\odot\,\mathrm{pc}^{-2}$), but to have a negligible effect at low densities. Wong & Blitz (2002) investigated the importance of this correction for the inner disks of several nearby galaxies, and found that introducing a density-dependent extinction correction increased the slope of the derived Schmidt law from $N \sim 0.8$ to $N \sim 1.4$. In a similar study Komugi et. al. (2005) showed that extinction corrections increased the slope of their derived Schmidt law from $N = 1.14$ to $N = 1.33$. However we would like to avoid if possible the use of the gas surface density itself to correct the SFRs, to avoid an obvious circularity in the calibration of the relation.

The advent of spatially-resolved infrared mapping of galaxies with *Spitzer* now allows us to attack the extinction problem head-on. As part of the SINGS project we have been exploring the use of hybrid optical + infrared extinction-free SFR indices (see Daniela Calzetti's review in this volume). In particular the use of a combination of Hα and 24 μm fluxes of HII regions provides a surprisingly robust means of deriving extinction-corrected Hα and ionizing fluxes. Variations in geometry limit the precicion of these corrections to a few tenths of a magnitude, but this is well suited to a statistical problem like the Schmidt law.

As a pilot application of this approach we have combined SINGS Hα, Pa α and 24 μm imaging of M51 with high resolution CO maps from the *Berkeley Illinois Maryland Array* Survey of Nearby Galaxies (*BIMA* SONG; Helfer et al. 2003) and HI maps from the *VLA* HI Nearby Galaxy Survey (THINGS; Walter

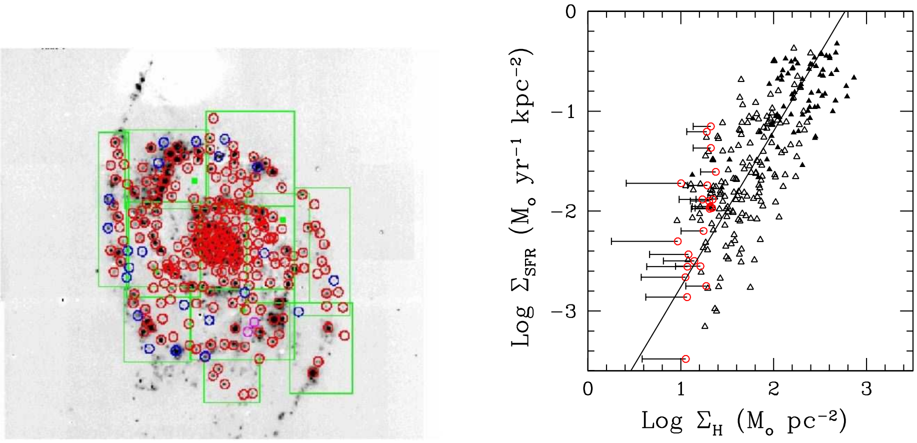

Figure 3. Left: Hα image of M51 with 520 pc measuring apertures overlaid. Right: Relationship between SFR surface density and total hydrogen surface density for the 257 star-forming regions in M51. Figures taken from Kennicutt et al. (2007), copyright AAS.

et al. 2005), to study the form of the star formation law on a point-by-point basis in the galaxy (Kennicutt et al. 2007). The left panel of Figure 3 shows an Hα image of M51 with the measuring apertures overlaid.

The righthand panel of Figure 3 shows the relationship between the extinction-corrected SFR per unit area and the total gas surface density for 257 star-forming regions in M51. Somewhat to our surprise there is a strong correlation, corresponding to a Schmidt law with slope $N = 1.57 \pm 0.04$. Apparently the disk-averaged law shown in Figures 1–2 is rooted in a local relationship between the SFR and gas surface densities on a region by region basis. We were restricted in this analysis to star-forming regions, rather than mapping the SFR at every pixel, in part because the signal/noise of our CO map is not sufficient to detect molecular gas between HII regions (only two CO peaks were observed outside HII regions), and because our method for deriving extinction-corrected SFRs breaks down outside of HII regions. However when we make the same comparison using 45″ (1850 pc) diameter apertures from the CO survey of Lord & Young (1990), which fully samples the disk, we also observe a tight Schmidt law, in this case with slope $N \sim 1.4$.

Figure 4 shows the SFR surface densities correlated separately with HI (blue asterisks) and CO-inferred H_2 surface densities (triangles). In this molecular rich galaxy the Schmidt law clearly is driven by a correlation between the SFR and the H_2 surface density, though we cannot distinguish whether this is because the molecular component is always more tightly correlated with the SFR, or whether it is simply because molecular gas happens to be the dominant mass phase in this galaxy. We hope to test this by applying the same analysis to galaxies where HI is a more significant constituent of the gas disk.

The large scatter in the Schmidt law shown in Figures 3–4 immediately raises the question of whether a second parameter other than gas density may be influencing the local SFRs. We tested for systematic trends with radius and

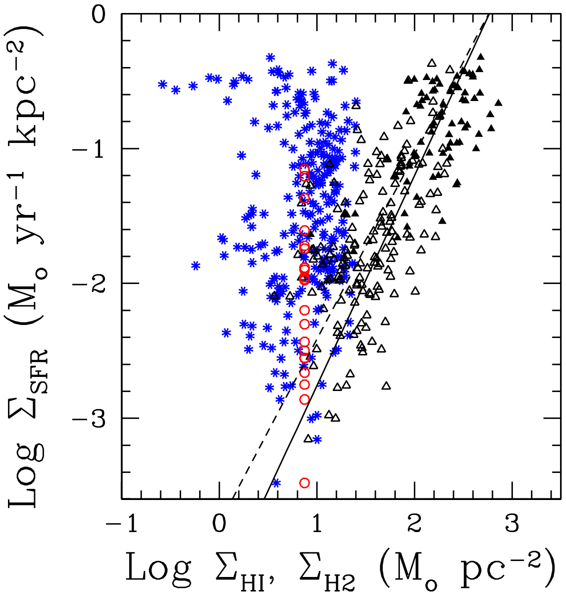

Figure 4. Relationship between the SFR surface density and the HI (asterisks) and H_2 (triangles) surface densities for the same regions in M51. Figure taken from Kennicutt et al. (2007), copyright AAS.

location in *vs* between spiral arms, and found no evidence for systematic differences. We suspect instead that the dispersion in the relation is partly or entirely due to random variations in extinction geometry, cluster age, and the population of the uppermost IMFs in the clusters, all of which will influence the amount of ionizing radiation per unit stellar mass being formed in the associations. We certainly cannot rule out an intrinsic dispersion in the Schmidt law itself, in addition to these effects.

5. Star Formation Thresholds

Spatially-resolved measurements of the SFR and gas surface densities also show evidence for a turnover or threshold in the star formation law at low gas densities. Qualitative evidence for such thresholds came with the first spatially-resolved HI maps of spiral and irregular galaxies, which often show emission extending far beyond the active star-forming disks of the galaxies. Such behavior could only be explained if the slope N of the Schmidt law were much steeper (larger) than the modest values of order $N \sim 1.5$ that are observed at higher gas densities. Kennicutt (1989) quantified this result by using Hα images of 15 galaxies to measure the radii at which the Schmidt law showed the threshold breaks; beyond the thresold radii star formation often persists, but with a much lower rate per unit surface density of gas. The results showed that the thresholds did not occur at a constant gas surface density, but instead varied by more than a factor of 10 in Σ_{crit}. He tentatively attributed the thresolds instead to a critical gravitational stability level (Toomre Q parameter) in the gas disk (also see Zasov & Simakov 1988). This analysis was subsequently extended to a larger sample by Martin & Kennicutt (2001), who also found evidence for Q thresholds, but with some evidence for systematic variations in Q_{crit} with galaxy type and a breakdown of the Q picture completely in low-mass galaxies with slowly rising rotation curves (also see below).

Over the past ten years this problem has received considerable attention, both observational and theoretical. A plethora of studies have confirmed the basic observation of thresholds, at least in the star formation traced by HII regions, in a variety of galaxy samples. However these new observations also suggest that the association of the thresholds with a critical surface density in the cold gas is considerably more complicated than suggested by the original observations. Probably the most important of the new results is a growing body of evidence for a breakdown of the constant Q interpretation of the thresholds in low-mass galaxies. Several authors have shown that in spiral galaxies with rising rotation curves, star formation can proceed efficiently even when the standard Q-criterion would predict that the disks should be in the sub-thresold regime (e.g., Thornley & Wilson 1995, Martin & Kennicutt 2001). Likewise in irregular galaxies, which tend to have rising rotation curves over the entire optical disk, the typical values of $\Sigma_{gas}/\Sigma_{crit}$ are lower by approximately a factor of two (e.g., Hunter, Elmegreen, & Baker 1998), consistent with the observations of low-mass spirals.

There is some disagreement over the interpretation of these observations. One interpretation is that the onset of star formation is still determined by local gravitational instabilities, but the threshold criterion is more complex than a simple isothermal disk Q criterion. Alternatives proposed include two-fluid instabilities (e.g., Jog & Solomon 1984, Elmegreen 1995, Martin & Kennicutt 2001) or shear (e.g., Kenney et al. 1993, Hunter et al. 1998). Others have suggested that non-gravitational mechanisms may be more fundamental in regulating the star formation. A promising alternative is a phase instability in the ISM, as proposed for example by Elmegreen & Parravano 1994, Schaye 2004). Distinguishing between these different threshold mechanisms can be challenging, because one can readily be triggered by the other, so one needs observations spanning a wide range of physical conditions to be able to separate them.

Most recently the very existence of the star formation thresholds has been called into question by some authors, following the observation with the *Galaxy Evolution Explorer (GALEX)* of extended ultraviolet disks in many nearby spiral galaxies (e.g., Thilker et al. 2005, Gil de Paz et al. 2005, Boissier et al. 2007). Since the UV emission extends well beyond the Hα threshold radii, some have suggested that the ionized gas thresholds do not represent transitions in the SFR at all. While admitting to some biases, I have not found these arguments to be convincing. HII regions extending well beyond the threshold radii have always been observed, and careful cross-comparisons with the ultraviolet sources shows no significant differences in the source properties (Zaritsky & Christlein 2007), apart from those produced by differential extinction between the UV and visible, small number sampling of O-stars in the faint clusters, and the much larger age range in the UV clusters. On the other hand these observations show clearly the superiority of the ultraviolet imaging for studying the extent and distributions of massive star formation in low surface brightness regimes. This may make it possible for the first time to study the form of the star formation law in the sub-threshold regime, though this will require careful analysis of the ultraviolet data to isolate the truly young clusters that are still associated with their parent gas clouds.

6. Concluding Remarks

In the latter part of this review I focussed not on what we understand about the star formation law but rather on the many areas where observations and theory have yet to converge. While this might seem discouraging at first, it actually is a very encouraging sign, the result of new data that are allowing us to confront the nature of the star formation law in a fundamental way, and begin to probe its underlying physics. As will be underscored in the panel discussion later in this conference, the combination of new multi-wavelength datasets with new physical insights makes this an exciting time for studying star formation in galaxies, and we can look forward to enormous progress during the next half of John Beckman's career.

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