

# Starbursts in Perspective: The Multi-Wavelength View of Star-Forming Galaxies

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Received 2005 December 30; accepted 2005 December 30

**Abstract** Thanks to the successful launches of the Spitzer Space Telescope and Galaxy Evolution Explorer, along with the completion of a host of large ground-based and HST-based optical surveys, we are in the midst of a revolution in our understanding of star formation in galaxies, and of starbursts in particular. This review provides a broad introduction to the properties and physical nature of starburst galaxies and extreme starbursts, in the context of the general population of star-forming galaxies.

**Key words:** galaxies: evolution — galaxies: starburst

## 1 INTRODUCTION

This is a most appropriate time to hold a conference dedicated to the subject of extreme starbursts near and far, because the subject is in the midst of an observational revolution. The Spitzer and GALEX missions are providing observations of unprecedented depth and completeness for hundreds of thousands of galaxies, covering the infrared and ultraviolet wavelengths where the bulk of the energy from young stars in galaxies is (re)emitted. Additional optical spectra and images are being provided by the 2dF and Sloan digital sky surveys, a host of groundbased H $\alpha$  imaging surveys, and numerous deep surveys of high-redshift objects from the ground and with the Hubble Space Telescope (HST). The potential of coordinated multi-wavelength observations is being fully exploited for the first time, most notably with the SINGS, SWIRE, and GOODS Legacy surveys on Spitzer. On the theoretical side, numerical simulations of galaxies are now including explicit treatment of gas cooling, star formation, and feedback processes, and when mated with semi-analytical models can produce synthetic datasets that can be compared directly to these new observations. With all of this new information accumulating our understanding of star formation in galaxies is being rebuilt on a new, stronger observational foundation, and with it we are gaining deeper understanding of the broader problems of galaxy formation and evolution.

This conference thus stands as a kind of mid-term report on what is being learned from these new surveys, with a special emphasis on the most extreme star-forming events found in galaxies, today and at earlier cosmological epochs. The program aptly illustrates the diversity of observational and interpretive approaches that are being brought to bear on this problem. With this in mind the organizers and I agreed that it would be appropriate to begin with an introductory review of starbursts, first addressing the definition and physical nature of starburst,

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and then considering what is meant by an extreme starburst— according to my own definition star-forming events that approach one or more physical limits in intensity or absolute star formation rate (SFR). I conclude with a brief description of some ongoing surveys of the local universe, including the Spitzer Infrared Nearby Galaxies Survey (SINGS), which are aimed at exploiting these new observational capabilities.

## 2 STARBURSTS: DEFINITIONS AND PROPERTIES

The origin of the term “starburst” dates back more than 20 years, to the early observations of dust-obscured star-forming regions in the centers of nearby galaxies (e.g., Rieke & Lebofsky 1979, Weedman et al. 1981), and the basic concept extends back much further (e.g., Hodge 1969, Searle et al. 1973, Huchra 1977, Larson & Tinsley 1978). Over the intervening years use of the term has broadened, to eventually encompass a diverse population of objects, spanning many orders of magnitude in SFR, whether expressed in absolute or normalized terms. This is aptly illustrated by the enormous number of names and acronyms that have been introduced to characterize particular types of starbursting systems: GEHRs, SSCs, HIIGs, ELGs, CNELGs, W-R galaxies, UVCs, UVLGs, BCGs, BCDs, LCBGs, LIGs (LIRGs), ULIGs (ULIRGs), HLIGs (HLIRGs), HUGs, LEGOs, E+A galaxies, K+A galaxies, nuclear starbursts, clumpy irregular galaxies, Lyman-alpha galaxies, LBGs, DRGs, EROs, submillimeter galaxies, SCUBA galaxies and others, including some I encountered for the first time at this conference! This bewildering array of terms is a reflection of the incremental way in which our understanding of starbursts has filtered down to us over the past three decades. Many of the classes were devised to define sources that were discovered in surveys at particular wavelengths, and their connection to the starburst phenomenon was only firmly established later. Surely the physical parameter space that characterizes starbursts must be simpler than this lexicon would suggest, and consequently some attempts have been made to define starbursts in more quantitative terms.

Conceptually we know that a starburst must be defined as a galaxy with an SFR that is far above its equilibrium rate, but how does one identify such objects? An obvious definition of a starburst is any galaxy with an absolute SFR greater than a specific amount. Surveys of local star-forming galaxies show that the SFR distribution function is well represented by a truncated power-law, with either an exponential (i.e., Schechter) or steeper power-law turnover (e.g., Gallego et al. 1995, Gronwall et al. 2004), with a turnover SFR\* in the range 3–5  $M_{\odot} \text{ yr}^{-1}$ . Consequently normal galaxies with SFR  $\gg 10 M_{\odot} \text{ yr}^{-1}$  are very rare, and this provides a physically meaningful absolute threshold for a starburst by this particular definition.<sup>1</sup> This limit can be understood physically. Observations show that the baryonic mass function of disk galaxies drops sharply below masses of order  $10^{11} M_{\odot}$ , and for a galaxy that forms stars at a constant rate over a Hubble time this translates to a maximum steady-state SFR of  $\sim 10 M_{\odot} \text{ yr}^{-1}$ . Consequently any galaxy observed with a present-day SFR much above this limit must be forming stars well above its equilibrium rate, a starburst by definition.

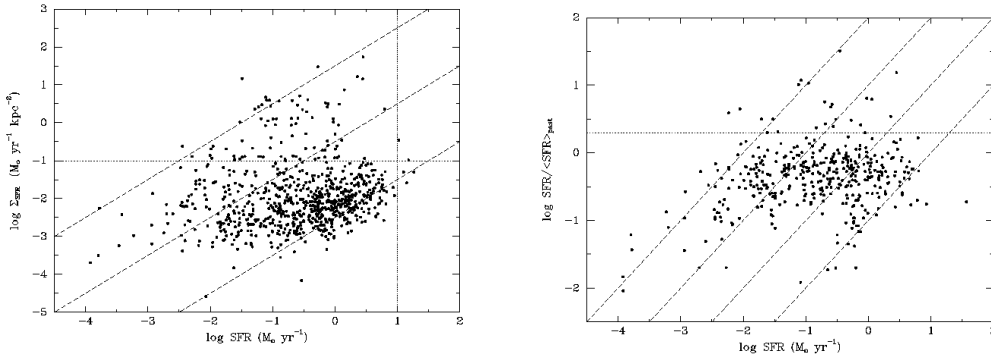
A familiar application of this type of definition is the use of infrared luminosity as a surrogate for identifying starbursts. A dusty star-forming galaxy with an infrared luminosity of  $10^{11} L_{\odot}$  (i.e., a Luminous Infrared Galaxy, or LIG) requires a SFR of  $\sim 17 M_{\odot} \text{ yr}^{-1}$  to produce this

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<sup>1</sup> Preliminary results from the GALEX project suggest that the form of the dust-corrected SFR distribution function may be lognormal, in which case there is no turnover (Martin et al. 2005). However the rarity of normal star-forming galaxies for SFR  $> 10 M_{\odot} \text{ yr}^{-1}$  applies, so the definition is still a reasonable one.

luminosity (Kennicutt 1998a), so LIGs (excluding AGN-heated objects) qualify as starburst galaxies by the definition given above.

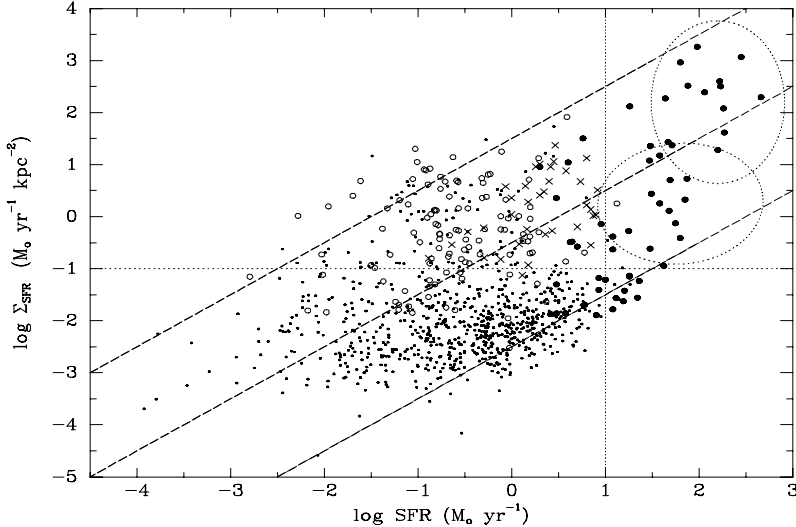
Defining starbursts solely in terms of absolute SFRs is inadequate, however, because it does not take into consideration the mass scale of the host galaxy. For example a supergiant spiral galaxy could have a large enough gas supply to sustain a steady-state SFR of  $>10 M_{\odot} \text{ yr}^{-1}$  over its entire lifetime, whereas an SFR of only  $1 M_{\odot} \text{ yr}^{-1}$  could be catastrophic in scale for a dwarf galaxy. Consequently it is also useful to parametrize starbursts in terms of normalized quantities, such as the SFR per unit area, SFR per unit stellar mass, or SFR per unit cold gas mass. There is a plausible physical basis for considering all of these definitions. It is now well established that the SFR per unit area is tightly correlated with the local gas surface density via a Schmidt law (see Sec. 3), while the SFRs per unit stellar and gas mass allow the current absolute SFR to be coupled to the average past SFR of the system and the future star formation timescale, respectively.



**Fig. 1** Left: Distribution of SFRs and SFR densities in local star-forming galaxies, as described in the text. Diagonal lines denote constant radius of the star-forming regions, from 0.1 to 10 kpc (top to bottom). Right: The same absolute SFRs, but in this case plotted against the ratio of the current SFR to average past SFR ( $b$ ). In this case the diagonal lines represent loci of constant stellar mass, ranging from  $10^8$  to  $10^{11} M_{\odot}$ . The horizontal and vertical dashed lines in both panels delineate the approximate boundaries between normal and starburst galaxies, as discussed in the text.

To illustrate how some of these definitions can be applied, Figure 1 shows the distribution of local star-forming galaxies in diagrams where the absolute SFR is plotted (on logarithmic scales) on the x-axis, versus the SFR per unit area and per unit stellar mass. In the left panel the SFRs are normalized to the deprojected areas of the star-forming disks themselves, and the right panel the SFRs per unit mass are expressed in the convenient dimensionless terms of the  $b$  parameter, i.e., the current SFR normalized to the average past SFR over the age of the disk. Diagonal lines each panel denote loci of constant radius and stellar mass, respectively. The data are taken from the 11HUGS survey, an  $H\alpha$  survey of galaxies in the local 11 Mpc volume (Kennicutt et al. 2006, in preparation), the  $H\alpha$  Galaxy Survey (James et al. 2004), and the GOLDMINE survey of the Virgo and Coma superclusters (Gavazzi et al. 2003). The SFRs were derived from  $H\alpha$  luminosities with a constant correction for extinction (1.1 mag, following Kennicutt 1983). The  $b$  parameters in the righthand panel of Figure 1 were derived from the observed  $H\alpha$  equivalent widths (EWs), following the methods given in Kennicutt et al. (1994). Note that these conversions are only approximately correct, particularly in terms of the

treatment of extinction on the  $H\alpha$  fluxes and EWs, but they are adequate for this application, where we are examining trends over orders of magnitude in various SFR measures.



**Fig. 2** Similar to Figure 1, except that we have overplotted 3 different types of starburst samples from the literature, luminous and ultraluminous star-forming infrared galaxies (large solid points), blue compact starburst galaxies (open circles), and circumnuclear starbursts identified in the optical (crosses). The reference sample from Figure 1 is plotted as small solid points. The upper and lower ellipses indicate the approximate loci occupied by high-redshift galaxies identified in the submillimeter and by the Lyman-break techniques, respectively.

These combined data provide a reasonable representation of the loci of star formation properties occupied by the normal galaxy population. A notable feature is the wide range of normalized SFR intensities at a fixed absolute SFR or *vice versa*. Nevertheless the bulk of the galaxy populations occupy relatively well-defined regions of the diagrams. For example the rapid turnover in the absolute SFR above  $10 M_{\odot} \text{ yr}^{-1}$  is clearly seen. Likewise the distributions of SFR per unit area (which we will refer to hereafter as SFR intensity, following common convention) and  $b$  can be approximately fitted with lognormal functions, but with a significant excess of objects with high SFRs. The boundaries between normal and starburst galaxies correspond to SFR intensities of order  $0.1 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  and  $b \simeq 2$ , as denoted by the horizontal lines in Figure 1.

We can compare these physical limits to the actual observed properties of various classes of starburst galaxies by plotting them on the same diagrams, and an example is shown in Figure 2. Three types of objects are superimposed on the same points as Figure 1, infrared-selected starbursts (all LIGs and ULIGs), with SFRs estimated from their total infrared luminosities, blue compact galaxies (BCGs), with SFRs estimated from  $H\alpha$  luminosities, and circumnuclear starbursts, with extinction-corrected SFRs derived from a variety of methods (Kormendy & Kennicutt 2004). In addition I show with ovals the approximate locations occupied by handfuls of Lyman-break galaxies and submillimeter-selected high-redshift galaxies that I was able to cull from the literature.

This diagram shows several interesting features. There actually is fairly good correspondence between the properties of the independently classified starbursts and the quantitative criteria

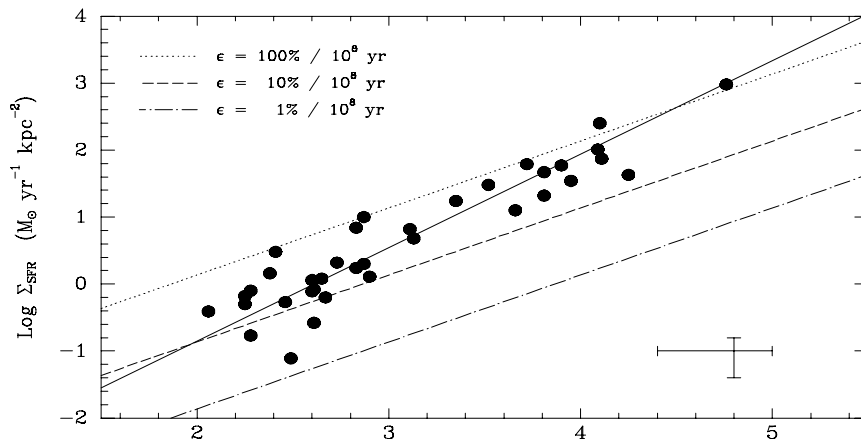
that we adopted earlier; although many of the starburst galaxies were identified without the aid of quantitative SFR measurements, they generally stand out from the main population of star-forming galaxies in these parametric plots. The addition of these objects also underscores the immense diversity in properties of star-forming galaxies even at the present cosmic epoch. For example we find among the infrared-luminous and ultraluminous galaxies objects with SFRs of  $20 - 1000 M_{\odot} \text{ yr}^{-1}$ , extending 100-fold the upper range found among normal galaxies. The diagrams also show that the most luminous starbursts are uniquely identified with very compact events, with typical radii in the range 0.1–1 kpc. Taken together this implies SFR densities that are comparable to those of dense stellar associations and star clusters in the cores of molecular clouds, but extending over regions of hundreds of parsecs and total SFRs of tens to hundreds of solar masses per year. It is interesting that these extreme parts of the diagram are also occupied by some of the high-redshift starburst galaxies, the submillimeter-selected objects in particular. This is but a preliminary comparison to illustrate the potential of this type of parametric comparison, and we will carry out more detailed comparisons as more data become available.

Yet another way to isolate starbursts is in terms of the local gas consumption times; if the SFR of a galaxy is so high that the available gas supply will be exhausted over cosmologically short timescales ( $\ll 1$  Gyr), then it must be a short-lived phenomenon by definition. Several authors have compared the gas masses and SFRs of starburst galaxies (see Sanders & Mirabel 1996 and Kennicutt 1998b for reviews), and an example comparison is shown in Figure 3, taken from Kennicutt (1998a). The diagram compares gas surface densities and SFR surface densities for 36 infrared-selected starbursts. The quantities are correlated via a Schmidt law, but also overplotted are dashed lines with gas consumption times of 0.1 – 10 Gyr. Most of the galaxies occupy the region between timescales of 100 Myr and 1 Gyr, which is comparable to the dynamical timescales of the parent galaxies (see next section), and factors of typically 10–30 shorter than the gas exhaustion times of normal star-forming galaxies (e.g., Kennicutt 1983, Kennicutt et al. 1994, Meurer et al. 2006).

### 3 EXTREME STARBURSTS?

The introduction of the term “extreme starburst” is recent, and to be honest I have not yet seen a physical definition offered in the literature. This grants me license to offer a few definitions of my own, all based on a common theme. Among the starburst galaxy population we often encounter objects that are forming stars near a maximum rate that is allowed by the physical properties of the host galaxy or the burst itself. These provide possible physical definitions of an extreme starburst, and in any case one can gain some valuable insights into the nature of starbursts by considering these limits.

*The “ELS” Limit:* One fundamental limit on the SFR rate of the galaxy is set by its gas mass and dynamical structure. Gas cannot assemble into the center of a galaxy on a timescale faster than a free-fall time, so an asymptotic SFR can be derived on the assumption that this gas is converted to stars with 100% efficiency over this timescale. Such bursts would be analagous to the primordial starbursts that formed the spheroids of galaxies in the scenario of Eggen, Lynden-Bell, and Sandage (1962; ELS). As has been pointed out by Lehnert & Heckman (1996), Kennicutt (1998a), and others, many infrared-luminous starburst galaxies lie near this limiting value. This fact by itself requires some kind of catastrophic event, such as a galactic merger, to fuel the most luminous observed starbursts; the ISM of galaxies simply do not collapse to within a few hundred parsecs of the galactic nuclei on this timescale by themselves!



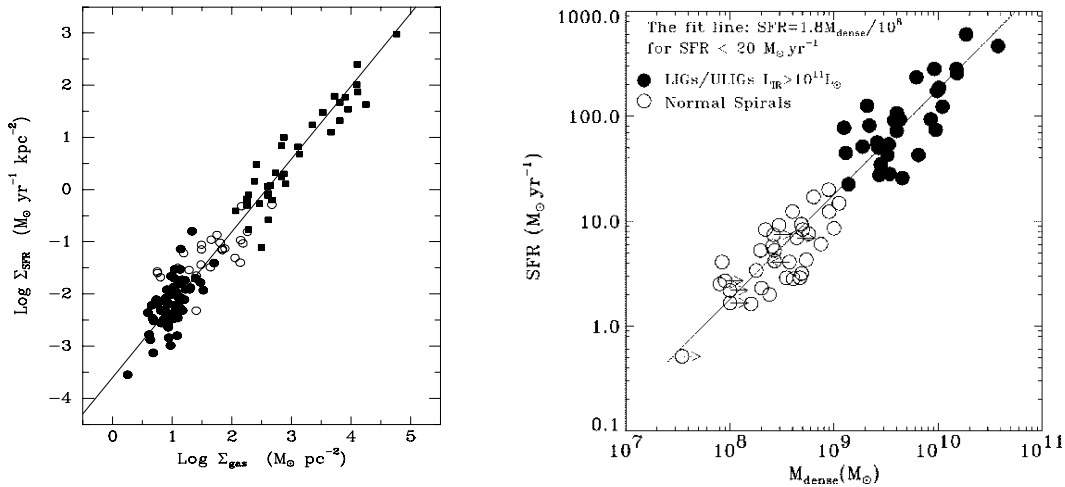
**Fig. 3** Relation between SFR density and gas density for 36 IR-selected starburst galaxies, intended here to show the range of gas consumption times, denoted by the diagonal lines and ranging from 100 Myr to 10 Gyr (top to bottom). Figure adapted from Kennicutt (1998b).

Of course there is now a well-established observational link between gas-rich mergers and these extreme starburst events (Sanders & Mirabel 1996 and references therein).

This consideration places a strong upper limit on the maximum SFR that one is likely to observe, at least in the present-day universe. If we take the extreme case of a pair of galaxies with a combined gas mass of  $10^{11} M_{\odot}$ , and the most rapid merger timescale that is plausible ( $\sim 10^8$  yr), this implies a maximum SFR of  $\sim 1000 M_{\odot} \text{ yr}^{-1}$ . One might be able to increase this slightly by invoking unusually massive and gas-rich host galaxies or an unusually rapid merger, but systems with SFRs of more than  $1000 M_{\odot} \text{ yr}^{-1}$  should be extremely rare. Therefore if you read papers claiming higher rates you should approach them with a healthy skepticism.

*Dust Radiation Pressure Limit:* Another important limit on the maximum SFRs in massive galaxies may be set by radiation pressure on the surrounding ISM. This has been discussed in depth recently by Murray et al. (2005). We know from the copious infrared emission of these starbursts that dust is abundant in these regions, and the opacity of this dust can set a luminosity limit that is analogous to the Eddington limit imposed by electron scattering in hot massive stars. Murray et al. argue that this will impose limits not only on the absolute SFR but also on the SFR intensity, with the limit becoming important at levels of order  $10^3 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ , comparable to the maximum levels observed (e.g., Figs. 2, 3). This mechanism may also be important in limiting accretion on to black holes and helping to determine the form of the black hole mass vs galaxy mass and velocity dispersion relations (Murray et al. 2005).

*Large-Scale Mass Loss and Galactic Superwinds:* Other forms of feedback from star formation may limit the intensities of the starbursts in lower-mass galaxies. Observations with the Chandra, XMM, and FUSE missions have revealed the preponderance of large-scale outflows and winds around starburst galaxies. This has been confirmed by groundbased interstellar absorption line measurements. These winds often show mass-loss rates that match or exceed the rate at which star formation is consuming the gas, and eventually the mass loss will quench the fueling of the starburst, and extreme cases may remove gas from the host galaxies permanently. See Veilleux, Cecil, & Bland-Hawthorn (2005) for a review of this rapidly developing field. Unlike the previous two examples where one can derive specific asymptotic limits to the SFR, the powering and onset of large-scale galactic winds appears to be much more complex,



**Fig. 4** Two forms of the Schmidt law in normal and starburst galaxies. The plot on the left is from Kennicutt (1998b), and correlates the SFR density with total gas density. The righthand plot from Gao & Solomon (2004) compares absolute SFRs with dense (mainly HCN) gas masses. Figures reproduced with permission of the AAS.

dependent on the SFR, its spatial and temporal concentration, and the structure of the surrounding ISM. As one might expect the effects of the wind appear to be the most pronounced in low-mass galaxies with low escape velocities, weak potential wells, and relatively diffuse ambient interstellar media. But there are indications from these studies that large-scale outflows become efficient in systems with  $\text{SFR} > 10 M_{\odot} \text{ yr}^{-1}$  and SFR intensities comparable to those that apply to starbursts (e.g., Rupke et al. 2005, Veilleux et al. 2005).

#### 4 CLUES FROM THE LOCAL UNIVERSE

Nearby galaxies, both starburst galaxies and normal, quiescent systems, have much to teach us about the starburst phenomenon as a whole. For the first time we are finally beginning to collect accurate SFRs for statistically robust samples of galaxies with well-defined selection properties. These make it possible to measure the incidence of starbursts and eventually to constrain the characteristic timescales, intensities, and recurrence timescales as functions of galaxy mass, type, and environment. The most comprehensive study of these local star formation demographics to date, focussing mainly on the normal galaxy population, is that of Brinchmann et al. (2004), based on a large sample of spectra from the Sloan survey. Our group at Arizona and Cambridge is involved in such work through the 11 Mpc  $\text{H}\alpha$  and Ultraviolet Galaxy Survey (11HUGS), which is obtaining  $\text{H}\alpha$  and deep GALEX UV imaging for a complete sample of galaxies in the local 11 Mpc volume (some of these data are shown in Figures 1–3). Janice Lee is investigating the burst properties of the dwarf galaxies in this sample for her Ph.D. thesis (Lee 2006, in preparation). In parallel the SINGG/SUNGG survey, led by Gerhardt Meurer at JHU, is obtaining deep  $\text{H}\alpha$  and GALEX imaging for an HI-selected sample of galaxies, to cover a larger cosmic volume and avoid the well-known selection effects that afflict optically-defined samples (Meurer et al. 2006, in preparation). All of these studies rely on accurate star formation diagnostics, and improved spectroscopic indicators have been developed by John Moustakas as part of his Ph.D. thesis (Moustakas et al. 2006), and multi-wavelength tracers are being developed as part of the Spitzer Infrared Nearby Galaxies Survey (SINGS) project (Kennicutt et al. 2003, Calzetti et al. 2005, Dale et al. 2005, Kennicutt et al. 2006, in preparation).

In view of the limited space I have chosen to highlight only one example of how observations of nearby galaxies can help us to understand these disparate starburst phenomena in a common physical framework. Figure 4 show two examples of SFR vs gas content relation in galaxies, on the left the SFR vs total density relation from Kennicutt (1998b), and on the right the SFR vs dense gas mass relation from Gao & Solomon (2004). In both cases the points plotted span the range from normal, quiescent star-forming galaxies to the most luminous starbursts known. The Schimidt law on the left shows a nonlinear slope ( $N = 1.4 \pm 0.1$ ) while the relation on the right is essentially linear ( $N = 1$ ). This suggests that the efficiency of star formation per unit core mass is a fundamental constant across this wide range of galaxy environments, and it must be the conversion efficiency of the ISM into these dense cores that varies across the spectrum of densities and SFRs, and is is responsible for the more efficient star formation in starbursts. Yu Gao will cover this subject at more length in his review in this volume. I offer it here only to remind that there do seem to be fundamental scaling laws that connect these various star-formation regimes, and they offer hope of building a deeper physical understanding of the processes that give rise to the extreme starbursts.

**Acknowledgements** It is a pleasure to thank Prof. Yu Gao and the local organizers of this conference and the NAOC in Beijing for their generous hospitality and support for my visit to China. I also gratefully acknowledge the support of my many collaborators on the SINGS, 11HUGS, and spectral atlas projects. Finally I gratefully acknowledge the financial support of the U.S. NSF through grant AST-0307386, NASA grant NAG5-8326, and the SINGS grant provided by NASA through JPL contract 1224769, which supported various portions of the results presented here.

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