Astronomy Department Faculty Publication Series   Astronomy

2009

The New Frontier: Galactic-Scale Star Formation

D Calzetti

University of Massachusetts - Amherst, calzetti@astro.umass.edu

The New Frontier: Galactic–Scale Star Formation

D. Calzetti[1], R. C. Kennicutt[2]

ABSTRACT

The arena of investigation of star formation and its scaling laws is slowly, but consistently, shifting from the realm of luminous galaxies to that of faint ones and to sub–galactic regions, as existing and new facilities enable investigators to probe regions of the combined parameter space of surface brightness, wavelength, and angular resolution that were inaccessible until a few years ago. We summarize what has been accomplished, and what remain as challenges in the field of galactic–scale star formation.

Subject headings: Galaxies; ISM

1. Introduction

Over the past two decades, evidence has been increasingly accumulating that there is a tight relation between the star formation rate surface density and the gas surface density *on global (disk–averaged) scales* in nearby galaxies, which is expressed, using the parametrization of Schmidt (1959, 1963), as:

$$\Sigma_{SFR} = A\Sigma_{gas}^{N}, \tag{1}$$

where Σ_{SFR} is in units of $M_\odot$ yr^{-1} kpc^{-2} and Σ_{gas} in $M_\odot$ pc^{-2}, and with N≈1.4–1.5 and A≈2.5×10^{-4} (e.g., Kennicutt 1998a, and references therein).

The scaling relation provides a direct link between the gas supply and the efficiency of the conversion process of gas into stars. Implicitly included in the physical mechanisms that regulate star formation is the threshold of star formation, i.e., the minimum gas surface density below which star formation cannot be initiated (e.g., Martin & Kennicutt 2001).

---

[1]Dept. of Astronomy, University of Massachusetts, Amherst, MA 01003; calzetti@astro.umass.edu

[2]Institute of Astronomy, Cambridge University, Cambridge, U.K.

Understanding the physical connection between star formation and its fuel is a critical ingredient for models of the evolution of galaxies and their baryonic component (e.g., Kay et al. 2002). A variety of physical models have been proposed to explain the power–law scaling between gas and star formation surface density and the presence of a threshold for star formation, including large–scale gravitational instabilities (Martin & Kennicutt 2001; Elmegreen 2002; Wong & Blitz 2002), local dynamical timescales of rotating disks (Wyse & Silk 1989; Kennicutt 1998a), galactic shear (Hunter, Elmegreen & Baker 1998), turbulence and cloud–cloud collision mechanisms or local gravity (Mac Low & Klessen 2004; Krumholz & McKee 2005; Tasker & Tan 2008; Heitsch& Hartmann 2008; Krumholz et al. 2009), and many others. These models cannot, however, be discriminated by global galaxy measures or by measurements that only target the brightest, most intense star–forming, and densest environments within galaxies.

The arena of investigation has been progressively shifting from large (global) scales to small (sub–kpc) scales and from bright to faint regions and galaxies in an attempt, among other things, to break this degeneracy, and determine the physical underpinning of the scaling laws of star formation. Over the past several years, studies have expanded the investigation of the relation between star formation and gas to radial profiles of galaxies, to constrain the form of the relation over a few kpc scales (e.g., Martin & Kennicutt 2001; Boissier et al. 2003; Schuster et al. 2006, and many others). Only with the relatively recent accomplishment of high spatial resolution mapping in CO and HI to probe the resolved molecular and atomic gas content of galaxies, and of homogeneous, arcsecond–resolution, UV–to–infrared multi–wavelength imaging surveys to derive robust dust–corrected SFRs, gas and star formation are beginning to the traced on the sub–kpc scales typical of star–forming regions in galaxies (Kennicutt et al. 2007; Bigiel et al. 2008; Leroy et al. 2008). These studies have also yielded larger variations in the index of the power law, with values in the range N≈1–3. This result underscores the fact that challenges are still present not only on the theoretical front, but on the observational front as well.

2. Star Formation Rate Tracers

At the most basic level, star formation rate (SFR) indicators are merely measurements of luminosity, either mono–chromatic or integrated over some specific wavelength range. The main target is to identify emission that probes recent star formation, while avoiding as much as possible contributions from more evolved stellar populations. This is generally accomplished by targeting continuum or line emission that is sensitive to the short–lived massive stars.

Luminosities at all wavelengths across the electromagnetic spectrum, from the X–ray to the radio, have been employed to calibrate SFR indicators, targeting both the direct stellar emission in the UV/optical range and the dust–reprocessed stellar light in the mid/far–infrared (Kennicutt 1998b; Calzetti 2009, and references therein). Because of observational limitations, SFR indicators at any wavelength have traditionally been reliably calibrated using the spatially–integrated light from luminous galaxies or luminous star–forming regions within galaxies. These calibrations have thus been luminosity–weighted towards the most active regions, also averaging across local variations in star formation history and physical conditions within each galaxy.

The main limitation for both spatially–integrated and spatially–resolved SFR indicators is the presence of dust, which absorbs the light from stars. Furthermore, dust is more closely associated with star–forming regions, and there is a loose correlation between amount of dust extinction and star formation activity in both star–forming galaxies and regions (Wang & Heckman 1996; Heckman et al. 1998; Calzetti et al. 2007). Uniform infrared surveys such as the one provided by IRAS (Soifer et al. 1986) have provided means to correct SFR indicators applied to whole galaxies.

Until recently, spatially–resolved measurements of SFRs had to rely on UV and/or optical tracers coupled to uncertain dust extinction corrections, due to the lack of high–angular resolution infrared measurements to probe the dust–obscured star formation. Over the past decade, however, the Infrared Space Observatory and the Spitzer Space Telescope have transformed our approach to sub–galactic SFR measurements, by probing the dust–obscured star formation with a few arcsecond resolution, corresponding to $\lesssim 1$ kpc size for galaxies within the Local Supercluster (Kennicutt et al. 2003; Calzetti et al. 2005, 2007; Calzetti 2009; Kennicutt et al. 2007, 2009). The soon–to–be–operational Herschel Space Telescope will expand on those capabilities, by spatially resolving dust–obscured star formation at the peak energy emission ($\sim$70 μm–150 μm).

Corrections for the effects of dust, however, can be challenging when applied over sub–kpc regions. For instance, the stars that are responsible for the UV emission in a star–forming region are often spatially separated from the gas that emit in Hα (and in the infrared), by a few tens to a few hundred pc (Calzetti et al. 2005; Relaño & Kennicutt 2009; Boquien et al. 2009a). Although this separation is irrelevant when measuring SFRs over entire galaxies, it becomes a crucial feature when the area over which the SFR is measured approaches the size of the star–forming region. In this case, the dust column density in front of the UV–emitting stars can be dramatically different from, and lower than, that in front of the Hα–emitting gas (Relaño & Kennicutt 2009), by possibly a larger factor than what inferred from galaxy–integrated studies (e.g., Calzetti, Kinney & Storchi–Bergmann 1994).

SFR measurements of spatially–resolved regions within galaxies depend on many other physical factors besides dust attenuation. Because SFRs defined at different wavelengths probe different timescales (e.g., the UV continuum emission probes stellar populations in the age range $\approx$0–100 Myr, while the Hα line emission probes the age range $\approx$0–10 Myr), factors such as local variations in the star formation history, star formation intensity, physical and chemical conditions, star cluster mass function, and stellar Initial Mass Function (IMF) are likely to play a role in the SFR calibrations.

A variety of studies have recently established that traditional SFR(UV) and SFR(Hα) calibrations (e.g., Kennicutt 1998b) yield different results when applied to bright or low–luminosity regions and galaxies. In bright galaxies SFR(UV)$\sim$SFR(Hα), implying that the underlying assumptions of those calibrations, i.e. constant star formation over the stellar age range of interest and a universal stellar IMF (e.g., Kroupa 2001; Chabrier 2003, or others), describe luminous galaxies reasonably well (e.g., Salim et al. 2007; Meurer et al. 2009; Lee et al. 2009). Variations in SFR(UV)/SFR(Hα) due to differences in the adopted stellar population models are around 10%–20%, which is well within the scatter of the measurements in bright galaxies. However, during the past decade, observational evidence has been accumulating that, as their luminosity decreases, galaxies display a systematic trend for SFR(UV) to become larger than SFR(Hα) (e.g., Sullivan 2000; Bell & Kennicutt 2001; Salim et al. 2007; Meurer et al. 2009; Lee et al. 2009). The discrepancy can be as large as an order of magnitude at the faintest end of the Hα luminosity, as shown by Lee et al. (2009) in an analysis of almost 350 galaxies within the local 11 Mpc[1]. Preliminary analyses appear to indicate a similar trend between bright and faint sub–kpc regions *within* galaxies (Boquien et al. 2009b). Furthermore, in the last few years GALEX has discovered the existence of extended UV disks in nearby star–forming spirals, extended well beyond the ionized gas disk (Thilker et al. 2005, 2007; Dong et al. 2008). Salim et al. (2007) attribute the UV 'excess' of low–luminosity galaxies to a luminosity–dependent excess attenuation correction in the UV data. More recently, Meurer et al. (2009) and Lee et al. (2009) have shown that the UV 'excess' in faint galaxies is present *prior to dust attenuation corrections.*

The existence of the problem is clear, but the determination of its nature will be considerably more difficult. Due to the different timescales they probe, the UV and Hα emission are sensitive to the star formation history of the region; in the case of an instantaneous burst of star formation with fixed stellar IMF and stellar population model, by the time the Hα intensity has decreased by two orders of magnitude, the UV has only decreased by a factor $\sim$6 (using the 2007–updated models of Leitherer et al. 1999). While the average star formation

---

[1]see, also, http://pompelmo.as.arizona.edu/$\sim$janice/11HUGS.html

history of whole star–forming galaxies may be approximated by simple models like constant or exponentially declining star formation, the star formation history of small areas within those same galaxies is likely to be more stochastic in nature. Nevertheless, star formation history may not be the only necessary ingredient, as environment–dependent stellar IMFs are also a possible explanation to the observed effects (Massey et al. 1995).

If variations in the star formation history may account for the observed discrepancies between SFR(UV) and SFR(Hα) for resolved regions within galaxies, the same approach is less applicable for large samples of low–luminosity and/or low–surface–brightness galaxies, where such variations are expected to average out or would imply implausible synchronizations among the galaxies (Hoverstern & Glazebrook 2008; Meurer et al. 2009). Alternative scenarios include a steepening of the high–end of the stellar IMF as a function of decreasing galaxy luminosity (Hoverstern & Glazebrook 2008; Meurer et al. 2009), and an environment–dependent star cluster mass function, for which less massive galaxies do not form massive gas clouds, leading to an stochastic sampling of the high end of the stellar IMF (Pflamm-Altenburg, Weidner, & Kroupa 2009; Lee et al. 2009). The two scenarios, albeit physically distinct, yield very similar observational results in terms of integrated fluxes or colors. A discrimination among the two will require direct (via star counts) measurements of stellar IMFs over the full parameter space of galactic environments, as found within the local $\approx$10–15 Mpc.

We are obviously in front of a severe limitation in our ability to apply standard calibrations of SFR indicators to sub–galactic regions. The challenge over the next few years will be to answer the following question: can we and how do we measure SFRs in spatially–resolved regions of galaxies?

3. Gas Tracers

The 21–cm line and CO emission are used to trace the neutral atomic and molecular gas (densities $\approx$300 cm^{-3}) components in galaxies, respectively. Denser molecular gas phases, $\gtrsim 3\times 10^4$ cm^{-3}, have been recently probed using tracers like HCN (Gao & Solomon 2004).

Surveys using existing facilities, like the VLA, WSRT, ACTA, CARMA, IRAM, Nobeyama, JCMT, etc. have, in recent times, produced or are producing homogeneous maps in HI and CO for nearby, luminous galaxies, in some cases with a few arcsecond resolution, to name a few, THINGS (Walter et al. 2008), BIMA–SONG (Helfer et al. 2003), HERACLES (Leroy et al. 2009), STING (Rahman et al. 2009).

While the need for homogeneously observed, reduced, and calibrated maps of large

samples of nearby galaxies is acute for both the atomic and molecular gas components, most of the challenges lay with the latter. Even with today' s facilities and instruments, most CO maps trace the bright central regions and spiral arms of luminous galaxies. Conspicuously absent, because generally undetected, are the interarm and outer regions of spiral galaxies and the dwarf and low surface brightness galaxies.

Those missing portions of the parameter space are due to the combination of two factors: (1) lack of sufficient sensitivity with existing facilities; (2) the uncertain relation between CO line intensity and molecular hydrogen column density. Maps of the nearby spiral NGC5194 obtained with the 45–m single–dish antenna of the Nobeyama Telescope (Koda et al. 2009) do indeed suggest that sensitivity to low–surface brightness emission is an important factor for detecting CO emission in faint galactic regions, possibly including the outer regions of large spirals. Observations with large single–antenna mm telescopes (e.g., the Large Millimeter Telescope, Perez-Grovas et al. 2006; Schloerb 2008) will be able to target low surface brightness emission in galaxies. In addition to the scaling laws, these maps will be instrumental for addressing the existence, universality, and environmental and physical dependences of the threshold of star formation in galaxies (e.g., Martin & Kennicutt 2001; Schaye 2004; Boissier et al. 2007; Dong et al. 2008; Krumholz & McKee 2008).

Far more complicated is determining whether a 'universal' relation between H_2 column density and CO luminosity (the X_{CO}–factor) is present in galaxies, and on which scales such relation would be applicable. Current determinations of X_{CO} are mainly based on measurements made in luminous, metal–rich spirals and range in value between 1.56 10^{20} and 4.0 10^{20} K km s^{-1} cm^2 (Bloemen et al. 1986; Strong et al. 1988; Young & Scoville 1991; Blitz & Rosolowsky 2006; Draine et al. 2007). One of the main caveats in the use of the X_{CO} factor is its potential dependence on metallicity (today still controversial, see, Wilson 1995; Boselli, Lequeux, Gavazzi 2002; Blitz & Rosolowsky 2006), and on the physical conditions of the molecular clouds (Dickman, Snell, & Schloerb 1986). One observational result is that the detectability of CO decreases sharply with galaxy parameters loosely linked to luminosity, or mass, or surface brightness (Meier, Turner & Beck 2002; Leroy et al. 2009). The self–shielding of CO is likely to decrease for decreasing metallicity, thus shrinking the physical size of the CO–emitting region in the molecular cloud. Studies of individual clouds in nearby galaxies covering the full parameter space of mass, luminosity, surface brightness, metallicity, etc. will be required to address these questions.

Independently of how reliably the CO traces H_2 under all or most conditions, searches for a complementary tracer of the molecular gas content of galaxies have become a timely endeavor. If the metal depletion on to dust is roughly constant from galaxy to galaxy, the expectation is that the dust–to–gas ratio will be proportional to the galaxy's or regions'

s metallicity; this has been shown to be in reasonable agreement with the data, with a factor $\sim$2 dispersion, at least in a sample of nearby galaxies (Draine et al. 2007). From that relation, the molecular gas content can be 'reverse engineered', once metallicity, HI mass and dust mass are known. To achieve this goal, accurate, sensitive, and high–angular resolution maps in both HI and dust emission will be required. Accurate determinations of dust masses on the scales relevant for probing the laws of star formation require observing, with $\sim$arcsec resolution, the full wavelength range from the infrared (starting around $\sim$10–30 μm) to the mm, where dust emission dominates over other processes. The Herschel Space Telescope only partially covers that requirement. The mm range is particularly important for measuring dust masses, since it probes the Rayleigh–Jeans tail of the black–body emission and is less sensitive to uncertain dust temperature(s) determinations (e.g., Dunne et al. 2000).

The infrared/mm emission, however, only traces heated (by stars) dust, and should, technically, provide a lower limit to the actual dust content of a galaxy or a region. In addition to dust emission, molecular gas content can in principle be traced via dust absorption, which is related to the dust column density if the extinction law of a galaxy or a galactic region is known (or reasonably determined, Bohlin, Savage & Drake 1978). The main difficulties in applying this method to external galaxies are: isolating and measuring individual stars, both extincted and unextincted, and determining the line–of–sight location of those stars relative to the gas distribution.

No less of an issue than measuring the spatially–resolved molecular gas content of galaxies is determining which gas density component is most closely associated with the star formation. Gao & Solomon (2004) determined that in equation 1 the exponent N$\sim$1 if dense gas only, as traced by HCN, is considered. The nature of the gas component most closely associated with the star formation is still matter of intense debate, both theoretical and observational (see, e.g., Blitz & Rosolowsky 2006; Kennicutt et al. 2007; Narayanan et al. 2008; Leroy et al. 2008). The biggest challenge for mapping the gas content of nearby galaxies and relating it to the physics of star formation remains securing uniform, high–spatial resolution, surveys of multiple gas tracers, probing different gas density phases, over a representative volume of the Local Universe.

4.   Summary

New windows are being opened across the electromagnetic spectrum in the combined parameter space of sensitivity and angular resolution by the refurbishment of the Hubble Space Telescope, the launch of the Herschel Space Telescope, and by the future space optical/infrared (e.g., the James Webb Space Telescope) and ground millimeter and radio

facilities (e.g., the Atacama Large Millimeter Array, the Large Millimeter Telescope, the EVLA, the Square Kilometre Array, etc.). These will enable the investigation of the accretion processes of neutral gas onto galaxies and of the physical mechanisms underlying the conversion of gas into stars, not only in our own Galaxy, but also in nearby and distant galaxies as a function of cosmic time.

With new opportunities come new challenges, both for star formation rate indicators and for gas tracers. As the focus of the field shifts from the analysis of galaxy–averaged quantities to spatially–resolved quantities within galaxies, calibrations of SFR indicators will have to be 'adapted' for applications to sub–galactic regions. This will imply accounting for variations in dust column densities within resolved regions, as well as variations in physical and chemical conditions, star formation histories and, possibly, determining any environmental dependence of the stellar IMF and cluster mass function.

For the gas tracers, challenges to be addressed over the next few years will include: determining whether the X_{CO} factor is universal or is dependent on local conditions, and isolating which parameters it may depend on; testing alternative ways to trace the molecular gas content in galaxies; securing large surveys of nearby galaxies with uniform, sub–kpc resolution maps covering the full parameter space of galaxy properties (luminosity, surface–brightness, mass, star formation intensity, global gas content, etc.), galactic conditions (including inter-arm regions of spirals, outer disk regions, etc.), and the full parameter space of gas conditions (density, metallicity, etc.) found in the Local Universe.

Addressing the issues discussed in this short review will have far–reaching consequences for a number of fields investigating galaxies and galaxy populations. For instance, it will both provide the tools to interpret observations of galaxies across cosmic times, from first light to the present, and input sub–galactic star formation prescriptions for numerical and analytical simulations of galaxy formation and evolution.

REFERENCES

Bell, E.F., & Kennicutt, R.C. Jr 2001, ApJ, 548, 681

Bigiel, F., Walter, F., Leroy, A., Brink, E., de Block, W.J.D., Madore, B., & Thornley, M.D. 2008, AJ, 136, 2846

Blitz, L., & Rosolowsky, E. 2006, ApJ, 650, 933

Bloemen, J.B.G.M., Strong, A.W., Mayer–Hasselwander, H.A., Blitz, L., Cohen, R.S., Dame, T.M., Grabelsky, D.A., Thaddeus, P., Hermsen, W., & Lebrun, F. 1986, A&A, 154, 25

Bohlin, R.C., Savage, B.D., & Drake, J.F. 1978, ApJ, 224, 132

Boissies, S., Prantzos, N., Boselli, A., & Gavazzi, G. 2003, MNRAS, 346, 1215

Boissier, S., Gil de Paz, A., Boselli, A., Madore, B.F., Buat, V., Cortese, L., Burgarella, D., Mũnoz–Mateos, J.C., Barlow, T.A., Forster, K. et al. 2007, ApJS, 173, 524

Boquien, M., Calzetti, D., Kennicutt, R.C., et al. 2009a, in preparation

Boquien, M., Calzetti, D., et al. 2009b, in preparation

Boselli, A., Lequeux, J., & Gavazzi, G. 2001, A&A, 384, 33

Calzetti, D. 2009, in the proceedings of the Conference'Dust Near and Far - 2008', Heidelberg, Germany, Sep. 2008, ASP Conference Series, in press

Calzetti, D., Kennicutt, R.C., Bianchi, L., Thilker, D.A., Dale, D.A., Engelbracht, C.W., Leitherer, C., Meyer, M.J., et al. 2005, ApJ, 633, 871

Calzetti, D., Kennicutt, R.C., Engelbracht, C.W., Leitherer, C., Draine, B.T., Kewley, L., Moustakas, J., Sosey, M., Dale, D.A., Gordon, K.D., et al. 2007, ApJ, 666, 870

Calzetti, D., Kinney, A.L., & Storchi–Bergmann, T. 1994, ApJ, 429, 582

Calzetti, D., Wu, S.-Y., Hong, S., Kennicutt, R.C., et al., 2009, in prep.

Chabrier, G. 2003, PASP, 115, 763

DIckman, R.L., Snell, R.L., & Schloerb, F.P. 1986, ApJ, 309, 326

Dong, H., Calzetti, D., Regan, M., Thilker, D., Bianchi, L., Meurer, G.R., & Walter, F. 2008, AJ, 136, 479

Draine, B.T., Dale, D.A., Bendo, G., Gordon, K.D., Smith, J.D.T., Armus, L., Engelbracht, C.W., Helou, G., Kennicutt, R.C., Li, A., et al. 2007, ApJ, 633, 866.

Dunne, L., Eales, S., Edmunds, M., Ivison, R., Alexander, P., & Clemens, D.L. 2000, MN-RAS, 315, 115

Elmegreen, B.G., 2002, ApJ, 577, 206

Gao, Y., & Solomon, P.M. 2004, ApJ, 606, 271

Heckman, T.M., Robert, C., Leitherer, C., Garnett, D.R., & van der Rydt, F. 1998, ApJ, 503, 646

Heitsch, F., & Hartmann, L. 2008, ApJ, 689, 290

Helfer, T.T., Thornley, M.D., Regan, M.W., Wong, T., Sheth, K., Vogel, S.N., Blitz, L., & Bock, D. C.-J. 2003, ApJS, 145, 259

Hoverstern, E.A., & Glazebrook, K. 2008, ApJ675, 163

Hunter, D.A., Elmegreen, B.G., Baker, A.L.1998, ApJ, 493, 595

Kay, S.T., Pearce, F.R., Frenk, C.S., & Jenkins, A. 2002, MNRAS, 330, 133

Kennicutt, R.C. Jr. 1998a, ApJ, 498, 541

Kennicutt, R.C. Jr. 1998b, ARA&A, 36, 189

Kennicutt, R.C., Armus, L., Bendo, G., Calzetti, D., Dale, D.A., Draine, B.T., Engelbracht, C.W., Gordon, D.A., et al. 2003a, PASP, 115, 928

Kennicutt, R.C., Calzetti, D., Walter, F., Helou, G., Hollenbach, D., Armus, L., Bendo, G., Dale, D.A., Draine, B.T., Engelbracht, C.W., et al. 2007a, ApJ, 671, 333

Kennicutt, R.C., Hao, C., Calzetti, D., et al. 2009, ApJ, submitted

Koda, J., & the Nearby Galaxies CO Survey Group, 2009, AAS, 213, 485.04

Kroupa, P. 2001, MNRAS, 322, 231

Krumholz, M.R., & McKee, C.F. 2005, ApJ, 630, 250

Krumholz, M.R., & McKee, C.F. 2008, Nature, 451, 1082

Krumholz, M.R., McKee, C.F., & Tumlinson, J. 2009, ApJ, in press (astroph/0904.0009)

Lee, Janice C., Gil de Paz, A., Tremonti, C. Kennicutt, R., Salim, S., Calzetti, D., Dalcanton, J., Dale, D., Engelbracht, C., Funes, J., Sakai, S., Skillman, E., van Zee, L. et al. 2009, in prep.

Leitherer, C., Schaerer, D., Goldader, J.D., González Delgado, R.M., Robert, C., Kune, D.F., de Mello, D.F., Devost, D., & Heckman, T.M. 1999, ApJS, 123, 3

Leroy, A.K., Walter, F., Brinks, E., Bigiel, F., de Blok, W. J. G., Madore, B., & Thornley, M. D. 2008, AJ, 136, 2782

Leroy, A.K., Walter, F., Bigiel, F., Usero, A., Weiss, A. et al. 2009, AJ, 137, 4670

Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188

Martin, C.L., & Kennicutt, R.C., Jr. 2001, ApJ, 555, 301

Mac Low, M.-M., & Klessen, R.S. 2004, RvMP, 76, 125

Meurer, G.R., Wong, O.I., Kim, J.H., Hanish, D.J., Heckman, T.M., Werk, J., Bland-Hawthorn, J., Dopita, M.A., Zwaan, M.A., Koribalski, B. et al. 2009, ApJ, 695, 765

Meier, D.S., Turner, J.L., & Beck, S.C. 2002, AJ, 124, 877

Narayanan, D., Cox, T.J., Shirley, Y., Davé, R. Hernquist, L., & Walker, C.K. 2008, ApJ, 684, 996

Perez–Grovas, A.S., Schloerb, F.P., Hughes, D., & Yun, M. 2006, SPIE, 6267E, 1

Pflamm-Altenburg, J., Weidnet, C., & Kroupa, P. 2009, MNRAS, 395, 394

Rahman, N., Bolatto, A., Wong, T., Leroy, A., Ott, J., Calzetti, D., Blitz, L., Walter, F., Rosolowsky, E., West, A., et al. 2009, AAS, 214, 310.06 (http://www.astro.umd.edu/STING)

Relaño, M. & Kennicutt, R.C., 2009, ApJ, in press (astroph/0905.1158)

Salim, S., Rich, M.R., Charlot, S., Brinchmann, J., Johnson, B.D., Schminovich, D., Seibert, M., Mallery, R., Heckman, T.M., Forster, K., et al. 2007, ApJS, 173, 267

Schloerb, F.P. 2008, SPIE, 7012E, 26

Schmidt, M. 1959, ApJ, 129, 243

Schmidt, M. 1963, ApJ, 137, 758

Schuster, K.F. Kramewr, C., Hitschfeld, M., Garcia-Burillo, S., & Moolerjea, B. 2007, A&A, 461, 143

Schaye, J. 2004, ApJ, 609, 667

Soifer, B.T., Sanders, D.B., Neugebauer, G., Danielson, G.E., Lonsdale, C.J., Madore, B.F., & Persson, S.E. 1986, ApJ, 303, L41

Strong, A.W., Bloemen, J.B.G.M., Dame, T.M., Grenier, I.A., Hermsen, W., Lebrun, F., Nyman, L.–A., Pollock, A.M.T., Thaddeus, P. 1988, A&A, 207, 1

Sullivan, M., Treyer, M.A., Ellis, R.S., Bridges, T.J., Liliard, B., & Donas, J. 2000, MNRAS, 312, 442

Tasker, E.J., & Tan, J.C. 2008, ApJ, submitted (astroph/0811.0207)

Thilker, D.A., Bianchi, L., Boissier, S., Gil de Paz, A., Madore, B.F., Martin, D.C., Meurer, G., Neff, S.G., Rich, R.M., Schiminovich, D. et al. 2005, ApJ, 619, L79

Thilker, D.A., Bianchi, L., Meurer, G., Gil de Paz, A., Boissier, S., Madore, B.F., Boselli, A., Ferguson, A.M.N., Mũnoz–Mateos, J.C., Madsen, G.J., et al. 2007, ApJS, 173, 538

Walter, F., Brinks, E., de Block, W.J.G., Bigiel, F., Kennicutt, R.C. Jr., Thornley, M.D., & Leroy, A. 2008, AJ, 136, 2563

Wang, B., & Heckman, T.M. 1996, ApJ, 457, 645

Wilson, C.D. 1995, ApJ, 448, L97

Wong, T., & Blitz, L. 2002, ApJ, 569, 157

Wyse, R.F.G., & Silk, J. 1989, ApJ, 339, 700

Young, J.S., & Scoville, N.Z. 1991, ARA&A, 29, 581