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Dust in External Galaxies

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Dust in External Galaxies

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Abstract. Existing (Spitzer Space Telescope) and upcoming (Herschel Space Telescope) facilities are deepening our understanding of the role of dust in tracing the energy budget and chemical evolution of galaxies. The tools we are developing while exploring the local Universe will in turn become pivotal in the interpretation of the high redshift Universe when near–future facilities (the Atacama Large Millimeter Array [ALMA], the Sub–Millimeter Array [SMA], the Large Millimeter Telescope [LMT], the James Webb Space Telescope [JWST]), and, possibly, farther–future ones, will begin operations.

1. Introduction

Many of the questions left open today by the Cold Dark Matter (CDM) framework of galaxy formation and evolution are nested into the basic understanding of the physical processes underlying star formation, as the baryonic matter sinks into the collapsing and merging dark matter haloes. These physical processes are the 'rules' for converting gas into stars and for driving the stellar and AGN feedback, which affect the evolution of the luminous and non–luminous baryonic component of galaxies (this being, ultimately, what we observe).

The open questions include, among others: the 'missing satellites' problem, for which CDM models predict about ten times, at least, more satellites around massive galaxies than what is actually observed (Moore et al. 1999); the 'characteristic baryonic mass scale' of galaxies, for which the observed luminosity function of galaxies follows the Schechter functional shape and has a characteristic stellar mass of $\sim 6\times 10^{10}$ $M_{\odot}$ (Kauffmann et al. 2003), in stark contrast with the scale–free, power–law functional shape of the CDM dark halos mass function (e.g., Benson et al. 2003); the 'angular momentum' (or 'overcooling') problem, for which the sizes of CDM model galaxies are smaller than what observed (e.g., Governato 2006); and the existence of bulge–less galaxies, again, difficult to produce within the CDM framework, where bulges are ubiquitous (Mayer et al. 2008).

Within this broad framework, the investigation of the infrared dust emission from galaxies offers a window on the questions revolving around star formation and feedback that is complementary to the UV–optical, 'direct stellar light' approach. Indeed, about 50% of the light observed in the Universe emerges at wavelengths longer than a few μm, and is due to dust–reprocessed stellar light (Hauser & Dwek 2001; Dole et al. 2006). More extreme still is the fraction of UV light, a probe of recent star formation, lost to dust absorption, this fraction being around 2/3–4/5 of the total UV from galaxies (Calzetti 2001).

The role of dust emission in tracing recent star formation becomes more important as the galaxy luminosity increases, since there is a loose correlation between star formation rate (SFR) and the amount of dust extinction measured in galaxies and galaxy regions (Figure 1; e.g., Wang & Heckman 1996; Heckman et al. 1998; Calzetti 2001; Hopkins et al. 2001; Sullivan et al. 2001; Buat et al. 2002; Calzetti et al. 2007). The most luminous, and most strongly star forming, galaxies in the Universe do tend to be infrared–bright (e.g., Sanders & Mirabel 1996; Smail, Ivison, & Blain 1997; Ivison et al. 1998; Blain et al. 2002), even after taking into account AGN contributions (Borys et al. 2995; Pope et al. 2008) and revisions to their infrared spectral energy distributions (SEDs; Pope et al. 2006). At the most basic level, accounting for the fraction of radiation from recent star formation absorbed by dust and re–processed in the infrared enables an accurate census of the total number of stars formed in galaxies across cosmic times, and a better understanding of the mass assembly of galaxies (Hopkins & Beacom 2006, and references therein).

Furthermore, the investigation of the dust components present in the outflows of galaxies, such as the recently detected Polycyclic Aromatic Hydrocarbon (PAH) emission in the wind of the starburst galaxy M82 (Engelbracht et al. 2006), may help understand the energetics of stellar feedback, and shed light on the 'pollutants' that can survive in the winds and possibly enter the intergalactic medium. Stellar feedback has been suggested as the 'culprit' of the mass–metallicity relation in galaxies (Garnett 2002; Tremonti et al. 2004), and the dust/gas ratio is correlated with the oxygen abundance in nearby star–forming galaxies (Draine et al. 2007).

2. Dust Emission and Dust Geometry

One common application, when measuring star formation in external galaxies, is to use the far infrared (FIR) dust emission as a measure of the dust–absorbed UV light, which then enables recovering the 'total' UV and quantifying the SFR as traced by the emission of young, massive stars.

Starburst galaxies show a well–defined correlation in the FIR/UV–versus–UV color plane (Figure 2 Meurer, Heckman & Calzetti 1999). The FIR/UV ratio is a measure of the UV attenuation suffered by the system: the higher the dust attenuation, the larger the amount of UV stellar energy reprocessed into the FIR by dust. Variations in the UV color probe the amount of dust reddening present in the system. Thus, in starbursts, the UV reddening is a good tracer of the total UV dust attenuation (Calzetti 2001).

Quiescent star–forming galaxies and regions show a $\sim$10 times larger spread in the FIR/UV ratio than starburst galaxies, at fixed UV color; the spread is in the sense that the starburst galaxies form the upper envelope to the quiescently star–forming systems (Figure 2 and Buat et al. 2002, 2005; Bell 2003; Gordon et al. 2004; Kong et al. 2004; Seibert et al. 2005; Calzetti et al. 2005). Thus, a far larger range of UV dust attenuations seems to be present in star–forming objects than in starbursts, for the same UV color. This is possible if in quiescent star–forming systems the reddening of the UV colors is not only a probe of dust, but also of ageing of the individual star–forming regions contribut-

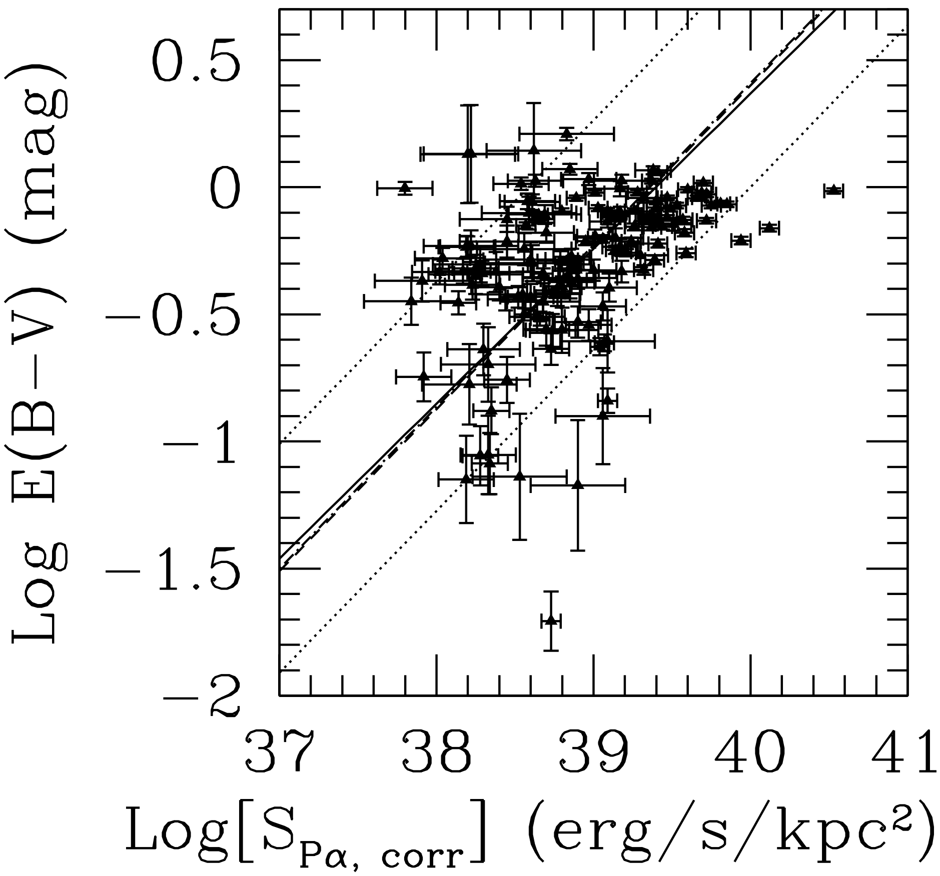

Figure 1. The dust attenuation, expressed as the logarithm of the color excess E(B−V)=A_V/3.1 (in magnitudes), as a function of the SFR density, in units of $M_\odot$ yr^{-1} kpc^{-2}, for 164 star–forming regions in 21 nearby galaxies. All the galaxies have metallicity close to the solar value. The continuous line is the expected trend after combining the Schmidt–Kennicutt law with the dust–to–gas ratio of the galaxies (Calzetti et al. 2007). The dotted lines are the 90% boundary to the datapoints.

ing to the UV emission in the system (regions up to an age of ≈100–300 Myr, Calzetti et al. 2005).

An heuristic scenario can be built by recalling that, within starbursts, the large number of supernovae can cause the remnants to merge together and behave as a 'collective entity', which can clear, thanks to the large input of mechanical energy, the interstellar medium within the starburst site and relocate the dust to the surrounding areas. In normal star–forming galaxies, such behavior is more fragmented and less energetic, as it takes place in individual HII regions, and the energy output is not as spatially concentrated as in starbursts. This can cause many of the young HII regions to remain dust–enshrouded for longer

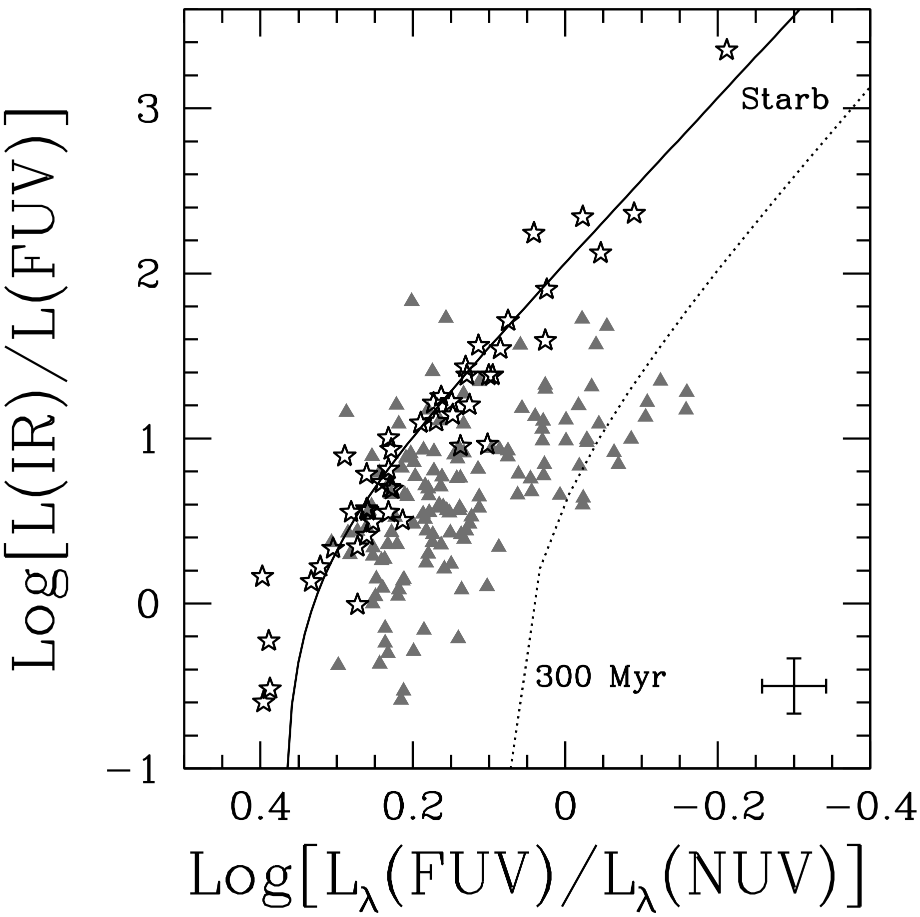

Figure 2. The FIR/UV ratio (the ratio of the far–infrared to the far–UV luminosity) versus the UV color (here expressed as the GALEX far–UV/near–UV color) for starburst galaxies and quiescently star–forming regions. The starburst galaxies are shown with star symbols. The grey filled triangles are star–forming regions within the galaxy NGC5194 (Calzetti et al. 2005). Redder UV colors correspond on average to larger FIR/UV ratios. The continuous line shows the best fit to the starburst galaxies, which is well represented by a model of a progressively more attenuated (from left to right) constant star–forming population. The dotted line shows the same dust attenuation trend for a 300 Myr old stellar population; this model represents a reasonable lower envelope to the NGC5194 star–forming regions, and to quiescent star–forming galaxies in general.

times than in starbursts. Secular motions will eventually separate them from their parent molecular cloud, but the stellar clusters will have aged while migrating to areas of lower dust column density. The presence of multiple mechanisms for changing the relative geometry of dust and stars in normal star–forming galaxies, and the fragmented nature of their star formation (HII regions behave like separate entities, and not like a collective one as in starbursts) is likely at the foundation of the observed spread in UV colors for constant FIR/UV ratio. Aged clusters can still be bright enough (at least relative to their younger, but more dust enshrouded, counterparts) to contribute to the measured UV emission in the normal star–forming galaxies, yielding 'red' UV colors (Figure 2) not because of dust attenuation, but because of age.

3. The Infrared Emission for Tracing Star Formation

The bolometric infrared emission from galaxies (integrated over the wavelength range $\lambda \sim$5–1000 μm) has been used as a SFR indicator at least since the data from the IRAS satellite showed that dust emission is widespread and significant in galaxies (Soifer et al. 1986). Young star–forming regions are dusty and the dust absorption cross–section peaks in the UV, i.e., in the same wavelength region where young, massive stars emission also peaks. Although the connection between SFR and infrared emission appears a straightforward one (e.g., Devereux & Young 1992), caveats have been raised for two major simplifications that underlie that connection (Hunter et al. 1986; Lonsdale Persson & Helou 1987; Rowan–Robinson & Crawford 1989; Sauvage & Thuan 1992). The first simplification is about the opacity of a galaxy: not all the luminous energy produced by recently formed stars is re-processed by dust in the infrared; in this case, the FIR only recovers part of the SFR, and the fraction recovered depends, at least partially, on the amount of dust in the system, as well as on geometry. Recipes that account for the light of young, massive stars not absorbed by dust have been recently proposed (Kennicutt et al. 2009): these recipes combine the infrared luminosity with the observed Hα luminosity, the latter a proxy for unobscured recent star formation, thus producing 'hybrid' SFR indicators.

The second simplification requires to neglect the heating of the dust by evolved, non–star forming populations; however, the latter will also contribute to the FIR emission, leading to an overestimate of the true SFR. If more evolved populations contribute mainly to the longer wavelength FIR, this extra contribution may be calibrated, at least for some classes of galaxies. A few approved observing projects for the upcoming Herschel Space Telescope plan to investigate this problem.

The connection between infrared emission and SFR also provides the underlying physical mechanism for the correlation between FIR and radio emission in galaxies over 5 orders of magnitude in luminosity (Helou, Soifer, & Rowan–Robinson 1985; Yun, Reddy, & Condon 2001). Recent analyses based on Spitzer data have shown that radio images are smoother versions of the infrared (70 μm) images of galaxies, with a correlation length that depends on the the age of the star formation event: cosmic rays created in more recent star formation events have not diffused significantly in the interstellar medium of galaxies (Murphy et al. 2006, 2008). The fundamental question of how two different processes, one related to the heating of dust by stars and the other affecting the propagation of the cosmic rays in galaxies, can produce a tight correlation over many orders of magnitude remains, however, open. The higher angular resolution images that will be provided by the Herschel Space Telescope in the FIR and by the EVLA in the radio will hopefully shed light on this fundamental question.

4. Mid–Infrared Emission from Galaxies

Spitzer's high angular resolution (a few arcseconds) in the mid–infrared has offered the opportunity to investigate this wavelength range with unprecedented detail, thus building on the foundation laid by the Infrared Space Observatory (ISO).

In particular, Spitzer has enabled a detailed investigation of the mid–infrared features in emission in the wavelength range ∼3–18 μm (e.g., Smith et al. 2004; Engelbracht et al. 2006; Wu et al. 2006; Dale et al. 2006; Smith et al. 2007; Draine et al. 2007; Galliano et al. 2008b). The dust emission in the mid–infrared ($\lambda \sim$5–40 μm) range is characterized by both continuum and bands. The continuum is due to dust heated by a combination of single–photon and thermal equilibrium processes, with the latter becoming more and more prevalent over the former at longer wavelengths (e.g., Draine & Li 2007, and references therein). The mid–infrared bands are generally attributed to Polycyclic Aromatic Hydrocarbons (PAH, Leger & Puget 1984; Sellgren 1984), large molecules transiently heated by single UV and optical photons in the general radiation field of galaxies or near B stars (Li & Draine 2002; Peeters, Spoon & Tielens 2004; Mattioda et al. 2005), and which can be destroyed, fragmented, or ionized by harsh UV photon fields (Boulanger et al. 1988; Pety et al. 2005).

Beyond being interesting in its own merit, the mid–infrared emission from galaxies has known renewed interest for its potential use as a SFR indicator in deep galaxy surveys, where the Spitzer (and Herschel) far–infrared bands correspond to rest–frame mid–infrared emission in high redshift galaxies (e.g., Daddi et al. 2005; Marcillac et al. 2006; Daddi et al. 2007). Furthermore, mono–chromatic SFR indicators avoid the uncertain extrapolations required by the bolometric infrared emission measurement, when only sparsely sampled dust SEDs are available (as often is the case for high–redshift data). The physical consideration underlying the use of the mid–infrared dust emission as a SFR indicator is that the dust heated by hot, massive stars can have high temperatures and will preferentially emit at short infrared wavelengths.

For the spectral regions where the dust SED is largely contributed by the PAH band emission, the definition of SFR indicators has been less than straightforward. The bands have shown to be heated by both recently formed (Roussel et al. 2001; Förster Schreiber et al. 2004; Dale et al. 2005, 2007) and evolved (Haas, Klaas & Bianchi 2002; Boselli, Lequeux & Gavazzi 2004; Bendo et al. 2008) stellar populations. The PAH emission in galaxies shows a strong correlation with the emission of the cold dust heated by the general (non–star–forming) stellar population (Haas, Klaas & Bianchi 2002; Bendo et al. 2008). In particular, Bendo et al. (2008) finds that the 8 μm emission is more closely correlated with the 160 μm emission (cold dust) than the 24 μm emission (warm dust) on 2 kpc scales in galaxies. Analysis of the Spitzer 8 μm data of very nearby galaxies, like NGC300 and NGC4631, shows that the PAH band emission highlights the rims of HII regions and is depressed inside the regions; this suggests that, even when closely associated with HII regions, the PAH dust is heated in the photo–dissociation regions surrounding HII regions and likely destroyed within the HII regions themselves (Helou et al. 2004; Bendo et al. 2006). In general, the impact of the non–star–forming populations on the heating of the 8 μm emission is at the level of a factor of about 2, in the sense that the 8 μm Spitzer band will be affected roughly by this amount of uncertainty when used as a SFR indicator (Calzetti et al. 2007).

Far more dramatic is the dependence of the PAH emission on metallicity (Engelbracht et al. 2005; Rosenberg et al. 2006; Wu et al. 2006; Madden et al. 2006). This dependence implies that regions with values about 1/10 $Z_{\odot}$ are about 10–30 times underluminous at 8 μm relative to regions with solar metallicity and same SFR (Figure 3, and Calzetti et al. 2007; Rosenberg et al. 2008). The observed correlation between the PAH 'deficiency' and the hardness of the interstellar radiation field (Madden et al. 2006) and the prevalence of 8 μm emission in the photo–dissociations regions surrounding the HII regions (Helou et al. 2004; Bendo et al. 2006) in nearby galaxies suggests that the strength/hardness of the radiation field influences the strength of the PAH emission, possibly by destroying or ionizing the carriers (Madden et al. 2006; Wu et al. 2006; Galliano et al. 2008b). A competing scenario suggests that in low–metallicity galaxies the deficiency of PAH emission carriers may be due to delayed formation, rather than destruction (e.g., Dwek 2005; Galliano et al. 2008a). In this scenario, PAHs are formed in the envelopes around carbon–rich Asymptotic Giant Branch stars, later injected in the interstellar medium over timescales of a few Gyr, while the other dust components are produced from supernova ejecta, which have timescales of a few to a few tens of Myr. If low–metallicity galaxies are intrinsically young systems, there will be a delay between the formation of the PAH emission carriers and the formation of all other dust components, thus accounting for the observed PAH emission 'deficiency'. However, this scenario counters the results from Hubble Space Telescope observations that show that even the supposedly least evolved galaxies in our local Universe harbor stellar populations that are at least a few Gyr old, and have been forming stars for at least that long (e.g., Leo A, Cole et al. 2007). Whatever the reason for the observed weakness of the PAH band emission in low–metallicity systems, the impact on SFR indicators based on spectral regions where these bands dominate the emission can be at the order–of–magnitude level, especially if applied to otherwise unknown systems (as can be the case in high–redshift surveys).

Conversely, spectral regions located at longer wavelengths, where thermal equilibrium emission starts to dominate over single–photon processes, become increasingly more effective at tracing recent star formation. This is the case, for instance of the Spitzer 24 μm band, for which many calibrations exist in the literature, applicable to HII regions, starburst–dominated galaxies, and normal star–forming galaxies (Figure 4, and Calzetti et al. 2005; Wu et al. 2005; Alonso–Herrero et al. 2006; Perez–Gonzalez et al. 2006; Calzetti et al. 2007; Relaño et al. 2007; Zhu et al. 2008; Rieke et al. 2009). All of these calibrations assume that the objects which the SFR indicator is applied to are negligibly contaminated by AGN emission. The 24 μm band has a much lower sensitivity to metallicity than the 8 μm emission, decreasing by just a factor 2-4 for a tenfold decrease in metallicity. This small decrease is fully accounted for by the increased transparency (lower dust–to–gas ratio) of the medium for lower metal abundances (Calzetti et al. 2007).

As in the case of the FIR emission, SFRs based on the 24 μm emission rely on the assumption that most of the light from massive, young stars is re–processed by dust in the infrared. This is generally not the case in most galaxies,

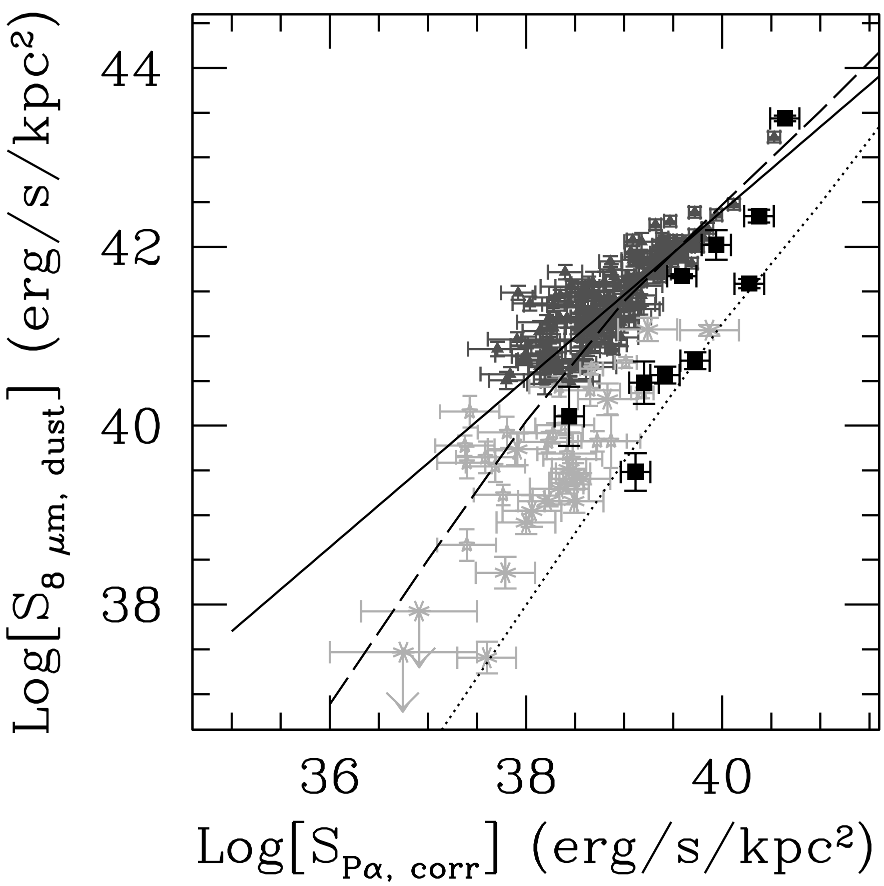

Figure 3. The luminosity surface density (LSD=luminosity/area) at 8 μm versus the Pα LSD of 10 starburst galaxies and 220 star–forming regions in 33 nearby galaxies (Calzetti et al. 2007). The 8 μm emission, from Spitzer images, has been corrected for stellar contribution. The Pα line emission (λ=1.876 μm) has been corrected for dust extinction, and is used as an unbiased tracer of massive stars SFR. Of the 220 regions, the ∼180 regions in high–metallicity galaxies, 12+log(O/H)>8.3, are marked in dark grey, and the ∼40 regions in low–metallicity galaxies are in light grey. The starburst galaxies (Engelbracht et al. 2005) are low–metallicity ones (black squares). The continuous line is the best fit to the high–metallicity star–forming regions (dark grey), with slope 0.94. Models for a young stellar population with increasing amount of star formation and dust are shown as a dash line ($Z=Z_\odot$) and a dot line ($Z=1/10\ Z_\odot$), using the stellar population models of Leitherer et al. (1999) and the dust models of Draine & Li (2007). The spread of the datapoints around the best fit line is well accounted for by a spread in the stellar population's age in the range 2–8 Myr.

and 'hybrid' SFR indicators are likely to be preferable to the use of a mono–chromatic SFR indicator. A hybrid SFR indicator that combines the observed

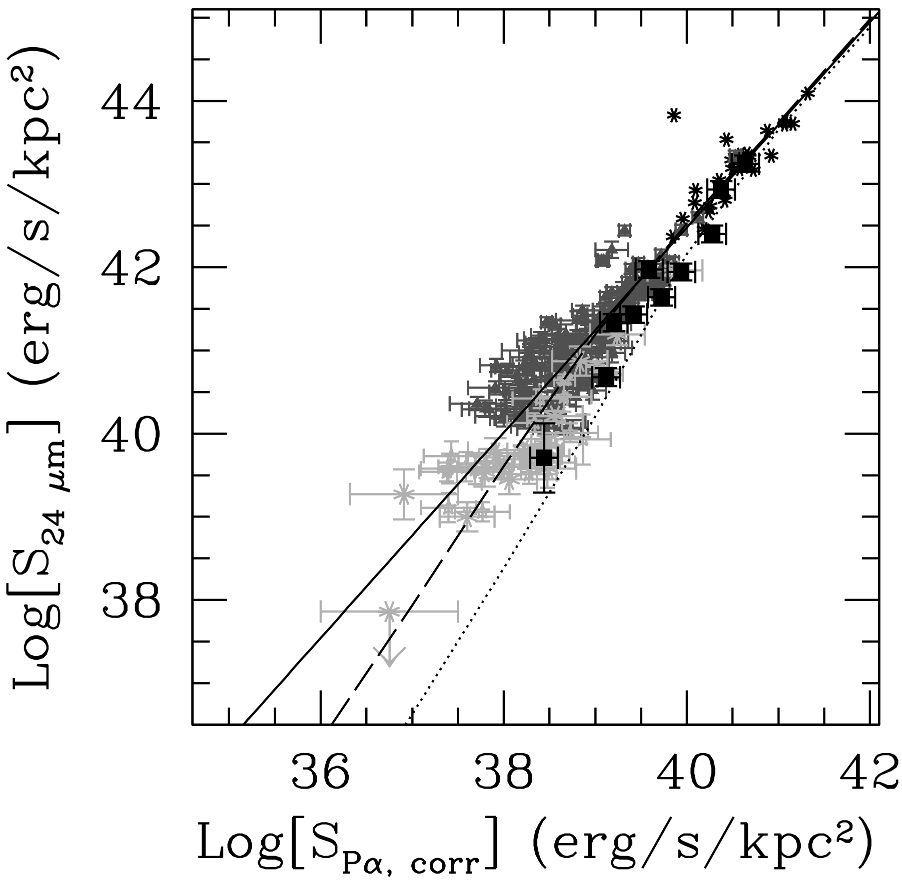

Figure 4. The same as Figure 3, with the vertical axis now reporting the 24 μm LSD, also from Spitzer. The black asterisks are the Luminous Infrared Galaxies (LIRGS) from Alonso–Herrero et al. (2006). The best fit line (continuous line) has slope 1.2.

Hα recombination line emission and 24 μm dust emission can account for both the dust–obscured star formation (traced by the dust emission) and the unobscured portion of the star formation (traced by the ionizing photons) (Figure 5, and Calzetti et al. 2007; Kennicutt et al. 2007; Zhu et al. 2008; Kennicutt et al. 2009). The proportionality factor between the Hα luminosity and the 24 μm emission changes from HII regions/starburst–dominated galaxies to normal star–forming galaxies. This is probably a reflection of the fact that the underlying stellar population that provides most of the UV–optical photons (which heat the dust) changes from one type of system to the other (Kennicutt et al. 2009).

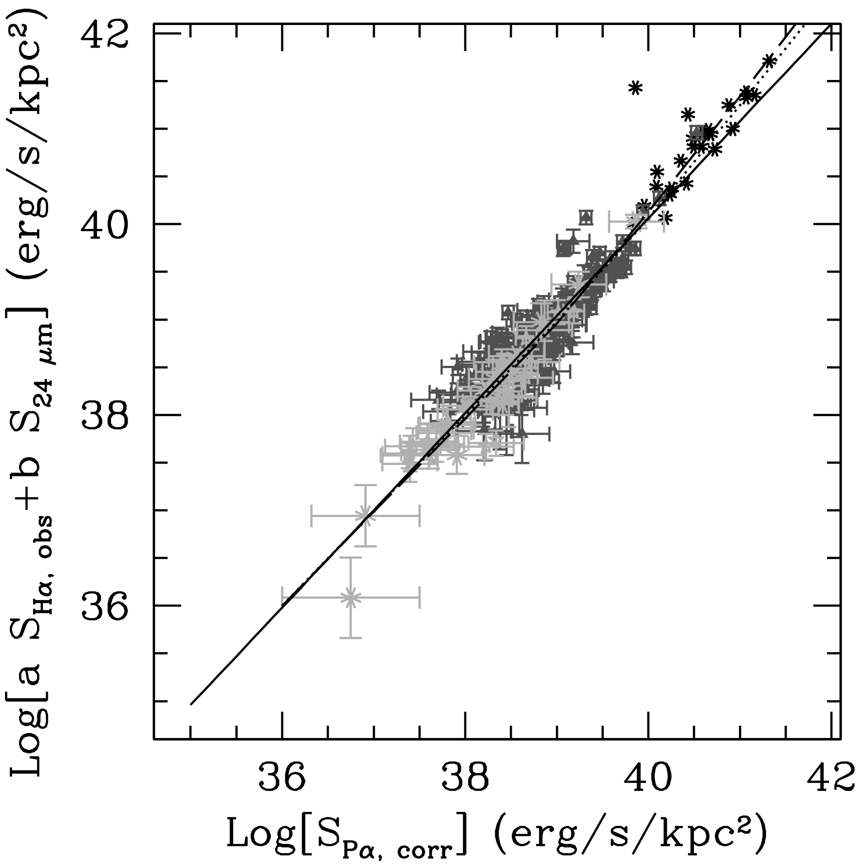

Figure 5. As in Figure 3, for the combined Hα and 24 μm LSD. The data follow the 1–to–1 line up to the LIRGs, for b/a=0.031 (Calzetti et al. 2007). For this SFR indicator, data and models are degenerate in metallicity. Here the 24 μm emission traces the dust–obscured SFR, and the Hα emission traces the unobscured SFR.

5. Summary

ISO and Spitzer have enabled major progress in our understanding of the relation between the stellar populations that heat the dust and the various dust emission components present in the mid/far–infrared.

The mid–infrared PAH emission is produced by dust grains transiently heated by both recently formed and evolved stellar populations, thus the use of this emission to trace SFRs is subject to large (about a factor of 2 or so) uncertainties. The same band emission is sensitive to metallicity, showing variations of factors 10–30 for changes of a factor of 10 in metallicity. The application of SFR indicators based on those emission bands to distant objects should thus be performed with care.

As we move to longer wavelengths, thermally heated dust increasingly contributes to the infrared emission. While still in the mid–infrared region (λ <40–50 μm), young, massive stars provide most of the heating for the dust, and this spectral region can be used reasonably well for tracing SFRs in galaxies. The main caveat here is that AGNs also contribute strongly to the heating of the dust emitting in the mid–infrared. Furthermore, all infrared–based SFR indicators need to rely on the assumption that most of the UV–optical light from stars is absorbed by dust, an assumption that is reasonably true only for luminous (L>10^{10} $L_{\odot}$) galaxies.

The combination of Spitzer 70 μm and radio data has enabled the investigation of the FIR–radio correlation at higher angular resolution than any earlier data, leading to the understanding that radio maps are smoother versions of the infrared maps of galaxies, and the 'diffusion' length of the cosmic rays correlates with the age of the star forming event. This is an area where the superior angular resolution of Herschel and EVLA will be able to unravel the underlying correlation between the processes that underlie the FIR and radio emission.

The Herschel Space Telescope, with its superior angular resolution in the far–infrared, will also enable the investigation of the role of the different stellar populations in the heating of the different dust components that characterize the mid/far–infrared emission. These will, in turn, enable accurate determinations of SFR indicators using the long–wavelength infrared emission, of dust masses, local radiation field intensities, dust opacities and temperature distributions for nearby galaxies, and of the grain size distribution and composition.

The information on the characteristics of the dust emission and underlying dust properties that is being and will be, in the near future, obtained for nearby galaxies is going to provide the 'toolbox' for the interpretation of distant galaxies that will be observed with Herschel, ALMA, SMA, and the USA–Mexico 50-meter millimeter telescope, the LMT.

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References

Alonso–Herrero, A., Rieke, G.H., Rieke, M.J., Colina, L., Perez-Gonzalez, P.G., & Ryder, S.D. 2006, ApJ, 650, 835

Bell, E.F. 2003, ApJ, 586, 794

Bendo, G.J., Dale, D.A., Draine, B.T., Engelbracht, C.W., Kennicutt, R.C., Calzetti, D., Gordon, K.D., Helou, G., Hollenbach, D., Li, AIgen, Murphy, E.J., et al. 2006, ApJ, 652, 283

Bendo, G.J., Draine, B.T., Engelbracht, C.W., Helou, G., Thornley, M.D., Bot, C., Buckalew, B.A., Calzetti, D., Dale, D.A., Hollenbach, D.J., et al. 2008 MNRAS, 389, 629

Benson, A.J., Bower, R.G, Frenk, C.S., Lacey, C.G., Baugh, C.M., & Cole, S. 2003, ApJ, 599, 38

Blain, A.W., Smail, I., Ivison, R.J., Kneib, J.-P., & Frayer, D.T. 2002, Ph Rev. 369, 111

Borys, C., Smail, I., Chapman, S.C., Blain, A.W., Alexander, D.M., & Ivison, R.J. 2005, ApJ, 635, 853
Boselli, A., Lequeux, J., & Gavazzi, G. 2004, A&A, 428, 409
Boulanger, F., Beichmann, C., Desert, F.–X., Helou, G., Perault, M., & Ryter, C. 1988, ApJ, 332, 328
Buat, V., Boselli, A., Gavazzi, G., & Bonfanti, C. 2002, A&A, 383, 801
Buat, V., Iglesias-Paramo, J., Seiber, M., Burgarella, D., Charlot, S., Martin, D.C., Xu, C.K., Heckman, T.M.,, Boissier, S., Boselli, A., et al. 2005, ApJ, 619, L51
Calzetti, D. 2001, PASP, 113, 1449
Calzetti, D., Armus, L., Bohlin, R.C., Kinney, A.L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
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
Cole, A.A., Skillman, E.D., Tolstoy, E. Gallagher, J.S., Aparicio, A., Dolphin, A.E., Gallart, C., Hidalgo, S.L., Saha, A., Stetson, P.B., & Weisz, D.R. 2007, ApJ, 659, L17
Daddi, E., Dickinson, M., Chary, R., Pope, A., Morrison, G., Alexander, D.M., Bauer, F.E., Brandt, W.,N., Giavalisco, M., Ferguson, H., et al. 2005, ApJ, 631, L13
Daddi, E., Dickinson, M., Morrison, G., Chary, R., Cimatti, A., Elbaz, D., Frayer, D. Renzini, A., Pope, A., Alexander, D.M., et al. 2007, ApJ, 670, 156
Dale, D.A., Bendo, G.J., Engelbracht, C.W., Gordon, K.D., Regan, M.W., Armus, L., Cannon, J.M., Calzetti, D., Draine, B.T., Helou, G., et al. 2005, ApJ, 633, 857
Dale, D.A., Gil de Paz, A., Gordon, K.D., Hanson, H.M., Armus, L., Bendo, G.J., Bianchi, L., Block, M., Boissier, S., Boselli, A., et al. 2007, ApJ, 655, 863
Dale, D.A., Smith, J.D.T., Armus, L., Buckalew, B.A., Helou, G., Kennicutt, R.C., Moustakas, J., Roussel, H., Sheth, K., Bendo, G.J., et al. 2006, ApJ, 646, 161
Devereux, N.A., & Young, J.S. 1992, AJ, 103, 1536
Dole, H., Lagache, G., Puget, J.-L., Caputi, K.I., Fernndez-Conde, N., Le Floc'h, E., Papovich, C., Prez-Gonzlez, P.G., Rieke, G.H., & Blaylock, M. 2006, A&A, 451, 417
Draine, B.T., & Li A. 2007, ApJ, 657, 810.
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.
Dwek, E., 2005, AIPC, 804, 197
Engelbracht, C.W., Gordon, K.D., Rieke, G.H., Werner, M.W., Dale, D.A., & Latter, W.B. 2005, ApJ, 628, 29
Engelbracht, C.W., Kundurthy, P., Gordon, K.D., Rieke, G.H., Kennicutt, R.C., Smith, J.-D. T., Regan, M.W., Makovoz, D., Sosey, M., Draine, B.T., et al. 2006, ApJ, 642, L127
Förster Schreiber, N.M., Roussel, H., Sauvage, M., & Charmandaris, V., 2004, A&A, 419, 501
Galliano, F., Dwek, E., & Chanial, P. 2008, ApJ, 672, 214
Galliano, F., Madden, S.C., Tielens, A.G.G.M., Peeters, E., & Jones, A.P. 2008, ApJ, 679, 310
Garnett, D.R. 2002, ApJ, 581, 1019
Gordon, K.D., Perez–Gonzalez, P.G., Misselt, K.A., Murphy, E.J., Bendo, G.J., Walfer, F., Thornley, M.D., Kennicutt, R.C., et al. 2004, ApJS154, 215
Governato, F. 2006, in The Fabulous Destiny of Galaxies: Bridging Past and Present, Proceedings of the Vth Marseille International Cosmology COnference eds. V. LeBrun, A. Mazure, S. Arnouts amd D. Burgarella (Paris: Frontier Group), 241
Haas, M., Klaas, U., & Bianchi, S. 2002, A&A, 385, L23
Hauser, M.G., & Dwek, E. 2001, ARA&A, 39, 249

Heckman, T.M., Robert, C., Leitherer, C., Garnett, D.R., & van der Rydt, F. 1998, ApJ, 503, 646
Helou, G.X., Soifer, B.T., & Rowan–Robinson, M. 1985, ApJ, 298, L7
Helou, G., Roussel, H., Appleton, P., Frayer, D., Stolovy, S., Storrie–Lombardi, L., Hurst, R., Lowrance, P., et al. 2004, ApJS, 154, 253
Hopkins, A.M., & Beacom, J.F. 2006, ApJ, 651, 142
Hopkins, A.M., Connolly, A.J., Haarsma, D.B., & Cram, L.E. 2001, AJ, 122, 288
Hunter, D.A., Gillett, F.C., Gallagher, J.S., Rice, W.L., & Low, F.J. 1986, ApJ, 303, 171
Ivison, R.J., Smail, I., Le Borgne, J.-F., Blain, A.W., Kneib, J.-P., Bezecourt, J., Kerr, T.H., & Davies, J.K. 1998, MNRAS, 298, 583
Kauffmann, G., Heckman, T.M., White, S.D.M., Charlot, S., Tremonti, C., et al. 2003, MNRAS, 341, 33
Kennicutt, R.C., Calzetti, D., Walter, F., Helou, G.,m 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, in prep.
Kong, X., Charlot, S., Brinchmann, J., & Fall, S.M. 2004, MNRAS, 349, 769
Leger, A., & Puget, J.L. 1984, A&A, 137, L5
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
Li, A., & Draine, B.T. 2002, ApJ, 572, 762
Lonsdale Persson, C.J., & Helou, G.X. 1987, ApJ, 314, 513
Madden, S.C., Galliano, F., Jones, A.P.,& Sauvage, M. 2006, A&A, 446, 877
Marcillac, D., Elbaz, D., Chary, R.R., Dickinson, M., Galliano, F., & Morrison, G. 2006, A&A, 451, 57
Mattioda, A.L., Allamandola, L.J., & Hudgins, D.M. 2005, ApJ, 629, 1183
Mayer, L., Governato, F., & Kaufmann, T. 2008, to appear in Advanced Science Letters (astroph/0801.3845)
Meurer, G.R., Heckman, T.M., & Calzetti, D. 1999, ApJ, 521, 64
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Murphy, E.J., Helou, G., Braun, R., Kenney, J.D.P., Armus, L., Calzetti, D., Draine, B.T., Kennicutt, R.C., Roussel, H., Walter, F., et al. 2006, ApJ, 651, L111
Murphy, E.J., Helou, G., Kenney, J.D.P., Armus, L., & Braun, R. 2008, ApJ, 678, 828
Peeters, E., Spoon, H.W.W., & Tielens, A.G.G.M. 2004, ApJ, 613, 986
Perez–Gonzalez, P.G., Kennicutt, R.C., Gordon, K.D., Misselt, K.A., Gil de Paz, A., Engelbracht, C.W., Rieke, G.H., Bendo, G.J., Bianchi, L., Boissier, S., Calzetti, D., Dale, D.A., et al. 2006, ApJ, 648, 987
Pety, J., Teyssier, D., Fosse‘, D., Gerin, M., Roueff, E., Abergel, A., Habart, E., & Cernicharo, J. 2005, A&A, 435, 885
Pope, A., Chary, R.-R., Alexander, D.M., Armus, L., Dickinson, M., Elbaz, D., Frayer, D., Scott, D., & Teplitz, H. 2008, ApJ, 675, 1171
Pope, A., Scott, D., Dickinson, M., Chary, R.-R., Morrison, G., Borys, C., Sajina, A., Alexander, D.M., Daddi, E., Frayer, D., MacDonald, E., & Stern, D. 2006, MNRAS, 370, 1185
Relaño, M., Lisenfeld, U., Perez-Gonzalez, P.G., Vilchez, J.M., & Battaner, E. 2007, ApJ, 667, L141
Rieke, G.H., Alonso-Herrero, A., Weiner, B.J., Perez–Gonzalez, P.G., Blaylock, M., Donley, J.L, & Marcillac, D. 2009, ApJ, in press (astroph/0810.4150)
Rosenberg, J.L., Ashby, M.L.N., Salzer, J.J., Huang, J.-S. 2006, ApJ, 636, 742
Rosenberg, J.L., Wu, Y., Le Floc'h, E., Charmandaris, V. Ashby, M.L.N., Houck, J.R., Salzer, J.J., Willner, S.P. 2008, ApJ, 674, 814
Roussel, H., Sauvage, M., Vigroux, L., & Bosma, A. 2001, A&A, 372, 427
Rowan–Robinson, M., & Crawford, J. 1989, MNRAS, 238, 523

Sanders, D.B., & Mirabel, I.F. 1996, ARA&A, 34, 749
Sauvage, M., & Thuan, T.X. 1992, ApJ, 396, L69
Seibert, M., Martin, D.C., Heckman, T.M., Buat, V., Hoopes, C., Barlow, T., Bianchi, L., Byun, Y.-I., Donas, J., Forster, K., et al. 2005, ApJ, 619, L23
Sellgren, K. 1984, ApJ, 277, 623
Smail, I., Ivison, R.J., & Blain, A.W. 1997, ApJ, 490, L5
Smith, J.D.T., Dale, D.A., Armus, L., Draine, B.T., Hollenbach, D.J., Roussel, H., Helou, G., Kennicutt, R.C., Li, A., Bendo, G.J., et al. 2004, ApJS, 154, 199
Smith, J.D.T., Draine, B.T., Dale, D.A., Moustakas, J., Kennicutt, R.C., Helou, G., Armus, L., Roussel, H., Sheth, K., Bendo, G.J., et al. 2007, ApJ, 656, 770
Soifer, B.T., Sanders, D.B., Neugebauer, G., Danielson, G.E., Lonsdale, C.J., Madore, B.F., & Persson, S.E. 1986, ApJ, 303, L41
Sullivan, M., Mobasher, B., Chan, B., Cram, L., Ellis, R., Treyer, M., & Hopkins, A. 2001, ApJ, 558, 72
Tremonti, C.A., Heckman, T.M., Kauffmann, G., Brinchmann, J., Charlot, S., White, S.D.M., Seibert, M., Peng, E.W., Schlegel, D.J., Uomoto, A., et al. 2004, ApJ, 613, 898
Wang, B., & Heckman, T.M. 1996, ApJ, 457, 645
Wu, H., Cao, C., Hao, C.-N., Liu, F.-S., Wang, J.-L., Xia, X.-Y., Deng, Z.-G., & Young, C. K.-S. 2005, ApJ, 632, L79
Wu, Y., Charmandaris, V., Hao, L., Brandl, B.R., Bernard-Salas, J., Spoon, H.W.W., & Houck, J.R. 2006, ApJ, 639, 157
Yun, M.S., Reddy, N.A., & Condon, J.J. 2001, ApJ, 554, 803
Zhu, Y.-N., Wu, H., Cao, C., & Li, H.-N. 2008, ApJ, 686, 155