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Nearby Galaxies with Spitzer

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Nearby Galaxies with Spitzer

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Abstract. We review the main advances brought by the Spitzer Space Telescope in the field of nearby galaxies studies, concentrating on a few subject areas, including: (1) the physics of the Polycyclic Aromatic Hydrocarbons that generate the mid–infrared features between ∼3.5 μm and ∼20 μm; (2) the use of the mid– and far–infrared emission from galaxies as star formation rate indicators; and (3) the improvement of mid–infrared diagnostics to discriminate between thermal (star–formation)and non–thermal (AGN) emission in galaxies and galaxy centers.

1 Introduction

The main paradigm shift brought by the Spitzer Space Telescope in the investigation of nearby galaxies stems from a combination of high (for infrared observations) angular resolution (∼2″–6″ at 8–24 μm), high sensitivity, and unprecedented mid–IR spectral–mapping capability. This has enabled the study of galaxies at the sub–kpc scale, thus resolving large morphological structures as traced by the dust emission and probing the ionization conditions of the interstellar medium (ISM) in those structures.

Landmark advances brought by Spitzer observations include: a deeper understanding of the nature of the Polycyclic Aromatic Hydrocarbon (PAH) emission features (formerly known as Unidentified Infrared Bands or Aromatic Features in Emission), and of the dependence of those features on the physical characteristics of the exciting stellar field (e.g., hardness of radiation) and the chemical characteristics of the ISM (e.g., metal content); a closer association between each dust emission component as a function of wavelength and the underlying heating stellar population, which, in turn, has led to better–calibrated mid– and far–IR star formation rate (SFR) indicators; a better understanding of the physics underlying the infrared–radio correlation of galaxies (Murphy et al. 2006, 2008); and important progress in the mid–infrared diagnostics to characterize and discriminate between star formation and active (non–thermal) galaxies and centers of galaxies. Many of these advances have enabled refinements of dust physics models, to better describe the shape and features of the dust infrared spectral energy distribution (SED, e.g., Draine & Li 2007).

Why are we interested in the investigation of the infrared emission from nearby galaxies? Emission in the infrared fine structure lines represents the main cooling channel for the ISM. Dust continuum emission represents about half of the global energy budget of the luminous component of the Universe (e.g. Hauser & Dwek 2001; Dole et al. 2006). This latter statement is, furthermore, SFR– and wavelength–dependent. As the SFR of galaxies increases, so does their dust opacity (e.g., Wang & Heckman 1996; Calzetti 2001; Sullivan et al. 2001), and about 80% of the UV light in the Universe is reprocessed by dust into the infrared. Clearly, a careful quantification of the impact of dust opacity on galaxy populations as a function of galactic parameters (morphology, luminosity, SFR, stellar population mix, gas content, metallicity, etc.) is a necessary step for recovering the stellar SEDs in those populations (e.g. Hopkins & Beacom 2006).

The Legacy from Spitzer in the field of nearby galaxies is, actually, still 'work in progress' in just about all the aspects of dust and ISM emission mentioned above. Furthermore, the Warm Spitzer Mission is obtaining extensive observations of nearby galaxies at 3.6 μm and 4.5 μm, thus probing the low–mass stellar populations in a dust–extinction–free wavelength range; these data promise to yield major progress in our understanding of the formation and evolution of galactic structures (rings, bars, arms, etc.) and the extended disks.

We present below a few highlights of the Spitzer results in the field of nearby galaxies; because of space limitations, however, this review will be mostly incomplete.

2 The Behavior of PAHs in Galaxies

By building on initial ISO results, Spitzer observations have placed on a secure footing the strong dependence of the intensity of the mid–IR PAH emission in galaxies on metallicity. The 8 μm–to–TIR luminosity ratio decreases by about an order of magnitude for a factor $\sim$10 decrease in metallicity, with a transition point 12+log(O/H)$\approx$8.1 (e.g., Boselli, Lequeux & Gavazzi 2004; Madden et al. 2006; Engelbracht et al. 2005; Hogg et al. 2005; Galliano et al. 2005; Rosenberg et al. 2006; Draine et al. 2007; Engelbracht et al. 2008; Marble et al. 2010). This decreasing trend is *on top* of the decrease in overall dust luminosity (at all wavelengths) that arises from the decreasing metal content.

Most works compare different galaxies over a range of metallicity values, but a few also analyze radial profiles of galaxies, finding basically the same result (Gordon et al. 2008; Muñoz–Mateos et al. 2009). Muñoz–Mateos et al. (2009) also suggests that the trend may revert for metallicity above 12+log(O/H)$\sim$9.0, although this result is tentative.

The nature of the correlation between PAH strength and metallicity is still debated. Some authors (e.g. Galliano et al. 2008; Dwek et al. 2009) suggest it may be due to the delayed formation of the PAH, which are thought to form in the envelopes of carbon–rich AGB stars. In a young system, the first dust will emerge from supernovae (timescale$<$10 Myr), while AGB–produced dust will emerge at a later stage (timescale$\approx$1 Gyr). This scenario may be difficult to reconcile with the fact that low–metallicity systems in the local Universe contain stellar populations that are typically older than 2 Gyr (see references in Tosi 2009). However, low–mass systems are also thought to lose most of their metals during the sporadic events of star formation that characterize their typical star formation history (e.g., Romano et al. 2006). The latter may play a role in restoring a 'delayed' dust enrichment of low–metallicity environments. The tentative reverse trend observed by Muñoz–Mateos et al. (2009) in metal–rich environments may also be accommodated within the evolutionary scenario for the PAH–metallicity dependence, a consequence of variations in the carbon relative abundance in AGB stars as a function of their mass and metallicity (Galliano et al. 2008).

An alternate scenario to the 'production' one calls for processing of PAHs by the radiation fields within which they are immersed (Boulanger et al. 1988; Madden et al. 2006; Gordon et al. 2008; Engelbracht et al. 2008). The original suggestion, based on the analysis of Milky Way nebulae, that the PAH emission is inversely correlated with the intensity of the stellar radiation field (Boulanger et al. 1988) is not confirmed, at least on large scales, by the analysis of a range of galaxy environments (Calzetti et al. 2007). Processing of PAHs by hard radiation fields has, thus, been proposed as a mechanism for the observed correlation between PAH luminosity and metallicity (Madden et al. 2006; Wu et al. 2006; Bendo et al. 2006; Smith et al. 2007; Gordon et al. 2008; Engelbracht et al. 2008), since low–metallicity environments are generally characterized by harder radiation fields than high–metallicity ones (e.g. Hunt et al. 2010). This suggestion agrees with the observation that PAHs are present in the PDRs surrounding HII regions, but are absent (likely destroyed) within the HII regions (Helou et al. 2004; Bendo et al. 2006; Relaño & Kennicutt 2009). A recent study of the SMC finds a high fraction of PAHs within molecular clouds (Sandstrom et al. 2010), thus complicating the interpretation of the formation/destruction mechanisms for these molecules. Overall, both production and processing may be driving the observed trend (Wu et al. 2006; Engelbracht et al. 2008; Marble et al. 2010).

Outside of HII regions and other harsh environments, PAHs tend to be ubiquitous. In particular, they can be heated by the radiation from the mix of stellar populations that contribute to the general interstellar radiation field (Haas, Klaas & Bianchi 2002; Boselli, Lequeux & Gavazzi 2004; Peeters, Spoon & Tielens 2004; Mattioda et al. 2005; Calzetti et al. 2007; Draine & Li 2007; Bendo et al. 2008). This suggests that PAH emission can be associated with evolved stellar populations unrelated to the current star formation in a galaxy.

3 Monochromatic SFR Indicators in the Infrared

The sensitivity and angular resolution of Spitzer have led to a new push in the derivation of SFR indicators based on a single IR band measurement, both for whole galaxies and for sub–galactic regions. The Spitzer deep surveys of distant galaxies have provided a strong reason for calibrating such indicators, since measurements of distant galaxies in the IR are often limited to one or a few wavelength measurements.

The rest–frame mid–infrared emission from dust in galaxies, in particular the emission detected in the 8 μm and 24 μm Spitzer bands (or the analogous ISO bands at 7 μm and 15 μm), has been analyzed by a number of authors (Roussel et al. 2001; Förster Schreiber et al. 2004; Boselli, Lequeux & Gavazzi 2004; Calzetti et al. 2005; Wu et al. 2005; Alonso–Herrero et al. 2006a,b; Perez–Gonzalez et al. 2006; Calzetti et al. 2007; Relaño et al. 2007; Zhu et al. 2008; Rieke et al. 2009; Kennicutt et al. 2009; Relaño & Kennicutt 2009; Salim et al. 2009), and a general correlation (but also a number of caveats) between mid–IR infrared emission and SFR has been found.

The restframe 8 μm dust emission generally shows a linear or almost–linear correlation with other SFR indicators (extinction–corrected hydrogen emission lines, bolometric infrared emission, etc.; Roussel et al. 2001; Förster Schreiber et al. 2004; Calzetti et al. 2005; Wu et al. 2005; Alonso–Herrero et al. 2006b; Calzetti et al. 2007; Zhu et al. 2008; Kennicutt et al. 2009; Salim et al. 2009). However, the calibration of the dust emission at 8 μm as a SFR indicator has been and still is a source of debate. The strong dependence on metallicity and/or hardness of the stellar radiation field, and the presence of PAH emission from dust heated by evolved stellar populations make such calibration difficult. The second contribution (the heating by evolved populations) is still unquantified, and we do not have a clear understanding of dependencies on morphology, stellar population mix, star formation rate, star formation intensity, etc. However, we can obtain a rough idea by converting the dust 8 μm mean luminosity density, $\sim 1.2\times 10^7$ L$_\odot$ Mpc^{-3}, within the local 10 Mpc (including emission from both PAHs and dust continuum, see Marble et al. 2010) to a volume SFR density, using metallicity–dependent linear calibrations to SFR(8 μm$_{dust}$) from the data of Calzetti et al. (2007). The result, ρ_{SFR}(8 μm$_{dust}$)$\sim$0.019 M$_\odot$ yr^{-1} Mpc^{-3}, is roughly 30%–60% higher than the commonly accepted values for the SFR density in the local Volume (see references in Hopkins & Beacom 2006); this indicates that on a global scale the 8 μm dust emission from galaxies traces the SFR with some excess, probably due to heating by evolved stellar populations (see, also, Alonso–Herrero et al. 2006b). On a galaxy–by-galaxy basis or, worse, on a sub–galactic region–by–region basis, such additional heating could be even more important.

The restframe 24 μm emission is more closely associated than the 8 μm emission with the dust heated by young, massive stars (Helou et al. 2004; Calzetti et al. 2005; Relaño & Kennicutt 2009), and should, therefore, provide a more accurate SFR indicator. The relation with SFR is, however, non–linear (Alonso–Herrero et al. 2006a; Perez–Gonzalez et al. 2006; Calzetti et al. 2007; Relaño et al. 2007; Kennicutt et al. 2009), which indicates, for galaxies up to a luminosity L(TIR)$\sim 5\times 10^{10}$ L$_\odot$, that increasing SFR produces both larger dust emission and higher dust temperatures. The scatter in the data is sufficiently large that linear fits through the data can be drawn, yielding fairly consistent calibrations among different authors: SFR(24)$\sim 2.0\times 10^{-43}$ L(24), with a dispersion in the calibration constant of about 40% for a Kroupa (2001) stellar IMF (Wu et al. 2005; Zhu et al. 2008; Rieke et al. 2009; Calzetti et al. 2010), with the SFR in M$_\odot$ yr^{-1} and L(24) in erg s^{-1}. For galaxies with luminosity higher than L(TIR)$\sim 5\times 10^{10}$ L$_\odot$, a non–linear correction to this relation is necessary, owing to dust self–absorption in these systems (Rieke et al. 2009).

Infrared–based calibrators, however, become inaccurate tracers of SFR in low metallicity/dust systems. A more effective way to trace SFRs across the full range of galaxy properties is to combine a tracer of obscured SFR (e.g., infrared) with a tracer of unobscured SFR (e.g., UV or optical, Calzetti et al. 2007; Kennicutt et al. 2007; Bigiel et al. 2008; Zhu et al. 2008; Kennicutt et al. 2009; Calzetti et al. 2010). For galaxies:

$$\begin{aligned} SFR &= 5.45\times10^{-42}[L(H\alpha)_{obs}+0.020L(24)], && L(24)<4\times10^{42}, \\ &= 5.45\times10^{-42}[L(H\alpha)_{obs}+0.031L(24)], && 4\times10^{42}\leq L(24)<5\times10^{43}, \\ &= 1.70\times10^{-43}L(24)\times[2.03\times10^{-44}L(24)]^{0.048} && L(24)\geq5\times10^{43}, \qquad (1) \end{aligned}$$

with SFRs and luminosities in units of $M_\odot$ yr^{-1} and erg s^{-1}, respectively [L(24)=νL(ν)$_{24\ \mu m}$; L(70), below, is defined similarly].

Dust emission at wavelengths longer than 24 μm also shows a generally linear correlation with SFR above ~0.1–0.3 $M_\odot$ yr^{-1}, but with a dispersion about the mean that increases with wavelength (Calzetti et al. 2010). The dispersion is about 25% (factor ~2) larger at 70 μm (160 μm) than at 24 μm. Independent analyses of the 70 μm emission from star–forming regions within galaxies, however, suggest that the emission at this wavelength is better (more tightly) correlated with SFR than either 8 μm, 24 μm or 160 μm emission (Lawton et al. 2010; Li et al. 2010). The discrepancy may be due to the presence, in the integrated light of galaxies, of contribution to the infrared emission from dust heated by diffuse, evolved stellar populations; this contribution may be around 30%–40% at 70 μm (Li et al. 2010) and larger at longer wavelengths (Draine et al. 2007; Calzetti et al. 2010). A better understanding of the contribution of the evolved stellar population to the dust heating in galaxies awaits the higher angular resolution data of the Herschel Space Telescope. For galaxies, the calibration at 70 μm is proposed as (Calzetti et al. 2010): SFR(70 μm)~5.9×10^{-44} L(70).

4 The Physics of the ISM

Mid-infrared spectroscopy by Spitzer has revolutionized our understanding of the physical characteristics of the interstellar medium within nearby galaxies. The literature is sufficiently vast to merit a separate review, and only a few salient points will be mentioned here.

Spitzer observations of silicate emission and absorption in Type 1 and 2 Seyferts, respectively, have provided strong support for the unification model for Active Galactic Nucleus (AGN) galaxies (Sturm et al. 2005; Siebenmorgen et al. 2005; Hao et al. 2005). Mid-infrared spectra of ULIRGs and QSOs have helped constrain the AGN fractional contribution to their bolometric luminosities (Veilleux, et al. 2009; Goulding & Alexander 2009). Spectroscopy from Spitzer has led to the improvement of mid-infrared diagnostics that characterize and distinguish between ULIRGs, AGN, and star–forming galaxies (Sturm et al. 2006; Dale et al. 2006; O'Halloran et al. 2006; Brandl et al. 2006; Spoon et al. 2007; Armus et al. 2007; Dudik et al. 2007; Hunter & Kaufman 2007; Farrah et al. 2007; Dale et al. 2009).

For instance, the ratio between the PAH features at 7.7 μm and 11.3 μm decreases for increasing hardness of the radiation field in AGNs, in contrast to the near–universal ratio observed in star–formation–dominated galaxy regions (Smith et al. 2007). In a similar vein, the line ratios [FeII](25.99 μm)/[NeII](12.81 μm) and [SiII](34.82 μm/[SIII](33.48 μm) are generally higher in AGNs than in star–formation–dominated regions, an effect that may be due to variations in the depletion factors of Si and Fe onto dust grains, or the ionization characteristics of the nebular gas around AGNs, or to X–ray photoionization processes (Dale et al. 2009).

Spitzer mid–IR spectroscopy has been instrumental in establishing that the low PAH abundance in low–metallicity galaxies is *not* due to the molecules being more highly ionized and/or dehydrogenated than in higher metallicity galaxies (Smith et al. 2007), although there is tentative evidence that they could be characterized by smaller sizes (Hunt et al. 2010). H_2 lines have been used to trace shocks and the excitation temperatures and masses of warm molecular hydrogen in galaxies (Devost et al. 2004; Higdon et al. 2006; Appleton et al. 2006; Roussel et al. 2007; Hunter & Kaufman 2007; Johnstone et al. 2007; Brunner et al. 2008). Finally, the abundances of neon and sulfur derived from mid–infrared spectroscopy have been compared with those from optical lines to establish the impact of dust obscuration within nearby galaxies (Wu et al. 2008; Bernard–Salas et al. 2009).

Finally, Spitzer has established that many elliptical galaxies show unusual mid-infrared spectra (Kaneda et al. 2005, 2008; Bregman et al. 2008) that may be related to the presence of X-ray emission from low luminosity AGN. Smith et al. (2007) suggest that the quiescent environments within ellipticals offer favorable conditions in which to observe these unusual spectra, since the mid-infrared spectra are not dominated by the effects of star formation typically seen in spiral and irregular galaxies.

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