HOT-DUST (690 K) LUMINOSITY DENSITY AND ITS EVOLUTION IN THE LAST 7.5 GYR

H. Messias1,2, B. Mobasher3, and J. M. Afonso1,4
1 Centro de Astronomia e Astrofisica da Universidade de Lisboa, Observatario Astronomico de Lisboa, Tapada da Ajuda, 1349-018 Lisbon, Portugal; hmessias@oal.ul.pt
2 Departamento de Astronomia, Av. Esteban Iturra 660 Piso, Facultad de Ciencias Fisicas y Matematicas, Universidad de Concepcion, Chile
3 Department of Physics and Astronomy, University of California, 900 University Avenue, Riverside, CA 92521, USA
4 Department of Physics, Faculty of Sciences, University of Lisbon, Campo Grande, 1749-016 Lisbon, Portugal

Received 2012 July 3; accepted 2013 August 20; published 2013 October 7

ABSTRACT

We study the contribution of hot-dust to the luminosity density of galaxies and its evolution with cosmic time. Using the Spitzer-IRAC data over an area of 1.8 deg2 covered by the Cosmic Evolution Survey (COSMOS) field, we estimate the contribution from hot-dust at rest-frame 4.2 μm (from 0 < z < 0.2 up to 0.5 < z < 0.9). This wavelength corresponds to blackbody temperature of \( \sim 690 \) K. The contribution of stellar emission is estimated from the rest-frame 1.6 μm luminosity (assumed to result from stellar emission alone) and subtracted from the mid-infrared luminosity of galaxies to measure hot-dust emission. To attempt the study of the 3.3 μm polycyclic aromatic hydrocarbon (PAH) feature, we use the rest-frame 4.2 μm to infer the hot-dust flux at 3.3 μm. This study is performed for different spectral types of galaxies: early-type, late-type, starburst, and IR-selected active galactic nuclei (AGNs). We find that (1) the decrease of the hot-dust luminosity density since 0.5 < z < 1 is steeper (by at least 0.5 dex) compared with that of the cold-dust, giving support to the scenario where galaxy obscuration increases with redshift, as proposed in the literature; (2) hot-dust and PAH emission evolution seems to be correlated with stellar mass, where rest-frame 1.6 μm luminous non-AGN galaxies (i.e., massive systems) show a stronger decrement (with decreasing redshift) in hot-dust and PAH emission than the less luminous (less massive) non-AGN galaxies; (3) despite comprising <3% of the total sample, AGN contribute as much as a third to the hot-dust luminosity density at z < 1 and clearly dominate the bright-end of the total hot-dust luminosity density function at 0.5 < z < 0.9; (4) the average dust-to-total luminosity ratio increases with redshift, while PAH-to-total luminosity ratio remains fairly constant; (5) at \( M_{1.6} > -25 \), the dust-to-total and PAH-to-total luminosity ratios increase with decreasing luminosity, but deeper data are required to confirm this result. Future study is necessary to further enlighten the characterization of the different spectral components at play in 2–5 μm spectral regime.

Key words: dust, extinction – galaxies: active – galaxies: evolution – galaxies: luminosity function, mass function – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Detailed knowledge of dust and its effect on the total bolometric luminosity of galaxies is essential for an unbiased study of the evolution of galaxies. For example, dust is often associated with star-formation activity, and, hence, any measurement of this requires correction for dust extinction (Silva et al. 1998; Buat et al. 2005; Bouwens et al. 2009). Furthermore, dust is directly correlated with the metallicity of galaxies and their chemical evolution (e.g., Calzetti et al. 2007). Because dust is produced mainly by supernovae (Rho et al. 2008; Barlow et al. 2010) or low/intermediate mass asymptotic giant branch (AGB) stars (Gehrz 1989; Ferrarotti & Gail 2006; Sargent et al. 2010), it also provides a clue toward studying stellar evolution in galaxies. Last, the knowledge of the effect of dust at high redshifts is important in studies of early formation of galaxies, their star-formation rates, and mass assembly (e.g., Hainline et al. 2011 and references therein).

Dust affects the output energy of galaxies by absorbing and re-processing their UV-to-optical light (produced by star forming regions or black-hole accretion), resulting in its re-emission mostly at far-infrared (FIR: \( \sim 70–500 \) μm throughout) wavelengths. Hence, the IR spectral regime (and the millimeter spectral regime at higher redshifts) has been most useful in unveiling the properties of dust in galaxies (for a review, see Hunt 2010). However, much of this work (e.g., Saunders 1990; Saunders et al. 1990; Blain et al. 1999; Scott et al. 2002; Greve et al. 2004, 2008; Ivison et al. 2005; Mortier et al. 2005; Magnelli et al. 2009; Clements et al. 2010; Jacobs et al. 2011) has relied on shallow data or small number statistics when compared with optical/near-infrared-based studies, even though stacking analysis has been used to lessen this problem (e.g., Chary & Pope 2010). Whereas the FIR/mm spectral range is sensitive to the cold-dust component (T \( \lesssim 100 \) K) found mostly in the interstellar medium (ISM), the hot-dust component (T \( \sim 500–1500 \) K), emitting mostly at \( \sim 1–8 \) μm, is closer to the heating source, thus being the front-line medium to absorb direct UV/optical light and trace the most active regions in galaxies.

Here, we perform a statistical study of the contribution of hot-dust and 3.3 μm polycyclic aromatic hydrocarbon (PAH) feature to the observed spectral energy distributions (SEDs) of different populations of galaxies and their evolution with redshift. The results here can be used to quantify the amount of UV/optical light obscuration in galaxies undergoing different degrees of star-formation or nuclear activity and its evolution with look-back time. This quantification is done by isolating the hot-dust component in galaxies and performing a statistical measurement of its luminosity density. Such a study requires wide-area, multi-band data. Particularly important is the availability of deep or medium-deep near- to mid-infrared (NIR, MIR) data (1–8 μm) tracing the hot-dust regime. These requirements are achieved by the observations from the IR array camera (IRAC; Fazio et al. 2004) on board the Spitzer Space Telescope (Spitzer;
Werner et al. (2004) covering the Cosmic Evolution Survey (COSMOS; Scoville et al. 2007).

The sample used in this study is described in Section 2, and the redshift estimates are presented in Section 3. In Section 4, we correct the aperture-to-total flux estimates as a function of redshift. Section 5 describes the method used to estimate dust and PAH emission, using SEDs for individual galaxies. The evolution of dust-to-total luminosity and PAH-to-total luminosity ratios are studied in Section 6. We present the dust and PAH luminosity density functions (LDFs), their dependence on galaxy types, and their evolution with redshift in Section 7.

The dependence on galaxy type and redshift is also shown for the overall dust and PAH luminosity densities in Section 8. Last, Section 9 summarizes the conclusions.

Throughout this article, we use the AB magnitude system.5 A ΛCDM cosmology is assumed with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

2. THE SAMPLE

We use observations from the COSMOS field, covering an area of 1.8 deg$^2$, with available multi-waveband data. The ultraviolet-to-IR coverage (0.15–8 $\mu$m) is unique, and there are, in total, 30 broad, intermediate, and narrow-band filters available (Table 1 in Ilbert et al. 2009, I09 henceforth).

For the present study, we use the $i^*$-band (Subaru Telescope) and 3.6 $\mu$m-selected catalogs described in I09. Our sample selection is based on flux cuts applied to the appropriate IRAC band-tracing the rest-frame 3.3 $\mu$m wavelength at a given redshift interval.

2.1. Galaxy Populations

We divide the galaxies in this study into early-type, late-type, starburst, and active galactic nuclei (AGNs), based on their SEDs. The non-AGN classification results from fitting galaxy SED templates to the observed galaxy SEDs as briefly described in Section 3 (see the detailed description in I09). For each galaxy, the best-fit template reveals its spectral type.

The AGN in our sample are color–color selected with the following criteria: $K_s - [4.5] > 0$ and $[4.5]-[8.0] > 0$ ($K_s +$ IRAC, K; Messias et al. 2012). Whenever the $K_s$-band is not available, sources are considered to be AGN when satisfying the Donley et al. (2012) criterion or when brighter than a rest-frame $K_s$ absolute magnitude of $M_{K_s} = -26$ (for the 211 sources in our sample with unavailable $K_s$-band photometry, 55 are IR AGN). No other spectral regime (X-rays, optical, or radio) is adopted to identify AGN hosts. The goal of this study is to independently trace IR emission due to hot-dust, induced by different radiation mechanisms. However, X-rays/optical/radio-selected AGN might reveal little of the hot-dust emission induced by the AGN itself, with the IR emission being potentially dominated by stellar light or dust emission from the host galaxy. The IR selection ensures that the hot-dust emission observed in AGN is induced mostly by nuclear activity.

2.2. Tracing Hot-dust Emission

This study focuses on two adjacent spectral regimes at rest-frame wavelengths 3.3 $\mu$m and 4.2 $\mu$m. These are chosen so that hot-dust emission continuum is traced in both regimes (corresponding to black-body temperatures of ~880 K and ~690 K, respectively), as well as the known PAH feature at 3.3 $\mu$m. By comparing the two adjacent spectral regimes, we aim to infer differences between hot-dust and PAH emissions and assess their evolution with cosmic time.

Although PAHs are not actual dust particles, they are large molecules of carbon rings (composed of ~50 carbon atoms) and hydrogen, which act as small dust grains significantly blocking UV radiation, producing broad emission features in the IR SEDs of galaxies (for a review, see Tielens 2011). Also, PAHs comprise a non-negligible fraction of the carbon existing in the universe (5–10 %) and are believed to be closely related to star-formation activity (Tielens 2011 and references therein).

The 4.2 $\mu$m spectral regime is free from PAH emission and traces only IR continuum because of dust heated by energetic radiation fields. Obscured star formation and AGN activity can account for such emission (da Cunha et al. 2008; Nenkova et al. 2008; Höög & Kishimoto 2010; Popescu et al. 2011 and references therein).

2.3. Sample Selection

The final samples are first selected on the basis of redshift criteria (Table 1) allowing the same rest-frame wavelength to be traced by each of the IRAC filters. The redshift intervals considered in this study are set by the target 3.3 $\mu$m rest-frame wavelength and the widths of the IRAC filters. Table 1 shows this study’s adopted redshift intervals that resulted from the specific redshifts where the 3.3 $\mu$m wavelength enters or leaves the 50% throughput limits of an IRAC filter. The rest-frame 4.2 $\mu$m wavelength is then traced by the contiguous IRAC filter at longer wavelengths relative to the band-tracing rest-frame 3.3 $\mu$m. As a result, the work is limited to the $z < 0.94$ range, where rest-frame 4.2 $\mu$m is possible to trace by the IRAC filter set.

We apply two completeness magnitude cuts to the resulting redshift selected samples. The first (upper panels in Figure 1) considers apparent magnitudes and is set as the brightest between the magnitude value at which the magnitude distribution starts to drop and the magnitude beyond which the fraction of sources with a redshift estimate (redshift completeness) is less than 0.7 (Section 3).

The second completeness magnitude cut (lower panels in Figure 1) considers rest-frame 1.6 $\mu$m absolute magnitudes (assumed to be dominated by stellar light alone) and takes into account the fact that it is not always possible to simultaneously

---

5 When necessary the following relations are used: $(K_s, [3.6], [4.5], [5.8], [8.0])_{AB} = (K_s, [3.6], [4.5], [5.8], [8.0])_{ Vega} + (1.841, 2.79, 3.26, 3.73, 4.40)$ from Roche et al. (2003) and http://faculty.ucr.edu/~gillianw/cal.html.
trace the rest-frame 3.3 μm and 4.2 μm for one galaxy. This is driven by the fact that rest-frame 4.2 μm is always traced by shallower data. This magnitude cut is set as the brightest value beyond which the fraction of sources with a hot-dust and PAH estimate drops below 0.7, and the value at which the magnitude distribution starts to drop. Hence, we consider all 0.05 < z < 0.19 sources with [3.6] < 23.56 and M_H < −16, all 0.21 < z < 0.52 sources with [4.5] < 23.75 and M_H < −20, and all 0.52 < z < 0.94 sources with [5.8] < 22.25 and M_H < −22. In this study, we did not consider sources that were flagged photometrically (e.g., resulting from blending or bad pixels), and we made no attempt at incompleteness correction regarding this rejection. The total counts for different populations are listed in Table 2.

3. REDSHIFT ESTIMATES

Whenever available, a spectroscopic redshift is assigned to galaxies. However, the bulk of the redshift estimates are photometric and are based on the broad-to-narrow-band photometry coverage available.

Briefly, the photometric redshifts are measured using a SED fitting procedure using the Le Phare code6 (S. Arnouts & O. Ilbert). The procedure applied on the COSMOS photometry data-set is described in I09. In the worst-case scenario for our sample (at z ∼ 1 and i^+ ∼ 25), the photometric redshift accuracy is expected to be \( \sigma_{\Delta z/(1+z_{\text{spec}})} \sim 0.05 \) (where \( \Delta z = z_{\text{spec}} - z_{\text{phot}} \)) and the percentage of outliers (sources with \( |z_{\text{spec}} - z_{\text{phot}}|/(1 + z_{\text{spec}}) > 0.15 \), denoted by \( \eta \)) is \( \eta \sim 20\% \) (I09).

Salvato et al. (2009, 2011, S11 henceforth) computed photometric redshifts for XMM-Newton- and Chandra-detected sources. Variability effects in X-ray AGN hosts are addressed before computing photometric redshifts, and SED templates accounting for AGN emission contribution are also adopted. This method provides photometric redshifts for the X-ray AGN sample with an excellent quality, reaching an accuracy of \( \sigma_{\Delta z/(1+z_{\text{spec}})} \sim 0.015 \) with an outlier fraction of \( \eta \sim 6\% \). One conclusion from this study was that below a given soft X-ray flux \( F_{0.5-2}\text{keV} = 8 \times 10^{-15} \text{erg s}^{-1} \), non-variable and/or morphologically extended X-ray sources do not require SED templates, taking into account AGN emission. However, the formula adopted in S11 should not be applied to X-ray-undetected sources, because intrinsically X-ray-luminous AGN might remain undetected as a result of high obscuration. The Appendix presents a detailed discussion of the photometric redshift quality for the IR-selected AGN sample (described in Section 2.1).

Some sources in the sample will have more than one redshift estimate resulting from different methods. The final redshift priority sequence (from highest to lowest) is as follows.

1. Spectroscopic redshifts with a probability larger than 90% of being correct from the zCOSMOS catalog, which considers only i^+ < 22 sources (Lilly et al. 2009).
2. Spectroscopic redshifts from Trump et al. (2009), Brusa et al. (2010), Fu et al. (2010), Kartaltepe et al. (2010), and Knobel et al. (2012), which provide additional spectroscopy for fainter sources.
3. Photometric redshifts from S11 for XMM-Newton- and Chandra-detected sources.
4. Photometric redshifts from I09 for non-IR-AGN sources.
5. A combination of photometric redshift solutions using non-AGN or AGN templates for IR-AGN sources as described in the Appendix.

In case the only redshift measurement is photometric, it is adopted only if the source has i^+ < 25 (as suggested by I09) and a good quality \( (z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{phot}}) < 0.4 \), with unflagged optical wavebands. The incompleteness that results from these quality constraints is accounted for while computing source densities (Section 7). This correction is given in Figure 2 for each of the IRAC bands used for sample selection (Section 2.3). The figure shows the variation of the fraction of sources with \( (z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{phot}}) < 0.4 \) and i^+ < 25, depending on observed magnitude in each of the IRAC channels. We do not consider sources fainter than the magnitude beyond which the redshift completeness is smaller than 0.7 (Figure 1). The redshift distribution is shown in Figure 3, highlighting the fraction of the sources with available z_{spec}, with i^+ < 24, with i^+ < 25, and the total population.

We note that by including only sources with i^+ < 25 in the study, highly obscured sources might have been missed. Nevertheless, Figure 4 shows that the i^+ > 25 population is composed mainly of starburst galaxies at z ≥ 1 (with the bulk...

---

**Table 2**

| zbin | TOTAL | EARLY | LATE | STARB. | AGN |
|------|-------|-------|------|--------|-----|
| 0.05 < z < 0.19 | 2954 | 514 (17) | 341 (12) | 2081 (70) | 18 (1) |
| 0.21 < z < 0.52 | 11439 | 2383 (21) | 3418 (30) | 5545 (48) | 93 (1) |
| 0.52 < z < 0.94 | 14435 | 3198 (22) | 4470 (31) | 6340 (44) | 427 (3) |

**Notes.** Numbers in parenthesis give the fraction (in %, approximated to unit) of the total population each population represents at each redshift interval.
the distributions of sources with available good quality spectroscopy (dashed not address the $z$ at Redshift distribution of the COSMOS sample. Highlighted are Figure 3.

![](image.jpg)

Figure 2. Completeness of reliable redshift estimates (i.e., fraction of sources with $(z_{\text{obs}} - z_{\text{spec}})/(1 + z_{\text{spec}}) < 0.4$ and $i^* < 25$), depending on source magnitude in each of the IRAC channels: $3.6$ μm (solid black line), $4.5$ μm (dotted blue line), and $5.8$ μm (dashed green line).

(A color version of this figure is available in the online journal.)

at $z \gtrsim 2$) or AGN at any redshift. Although this work does not address the $z \gtrsim 1$ regime (Table 1), extremely obscured AGN at $z \lesssim 1$ with $i^* \gtrsim 25$ will be missed. At this stage, one can estimate only an upper limit of the $i^* \gtrsim 25$ AGN by considering all sources inside the KI region to be AGN (they can also be $z \gtrsim 2.5$ starbursts). This yields a 32% rejection of the KI population when applying the $i^* < 25$ cut. Because the redshift of the faint KI-selected sources is unknown, we add in quadrature a 0.32 factor to the error budget while estimating AGN source densities (see below). This value is conservative, given that not all KI sources with $i^* \gtrsim 25$ are AGN at $z \lesssim 1$.

When computing measurement-associated errors, we consider in quadrature Poisson- and $z_{\text{phot}}$-induced errors ($\sigma_{\text{pois}}$ and $\sigma_{\text{phot}}$, respectively) and a factor ($f_o$) to account for photometric redshift outliers (we adopt a conservative value of $f_o = 0.2$, 109 and the Appendix). In the case of the AGN sample, an additional factor ($\sigma_{\text{spec}}$), accounting for the AGN with $i^* \gtrsim 25$, should be considered. For example, the error associated to source density for the AGN sample is the following: $\sigma_{\rho} = \sqrt{\sigma_{\rho,\text{spec}}^2 + \sigma_{\rho,\text{phot}}^2 + (f_o^2 + f_{\text{phot}}^2)\rho^2}$, where $\rho$ represents the source density.

4. APERTURE PHOTOMETRY CORRECTION

We note that the reference IRAC photometry used to select our sample was measured using an aperture of 1.9 and then scaled to total flux using a correction factor assuming a point source. However, such assumption is not always verified, especially at low redshifts. At such distances, the physical size traced by a 1.9 aperture is small ($<6$ kpc; Table 1), thus probing only the central region of a galaxy.

Hence, we apply a statistical correction to the four IRAC bands depending on redshift and spectral type (only for non-AGN populations) by comparing them with the 4.1 aperture (ap4) photometry. Figure 5 shows the magnitude difference between the two apertures versus the 1.9 aperture (ap2) magnitude. Each panel refers to different redshift bins where the rest-frame 3.3 μm is traced by the IRAC bands. Note, however, that the corrections are applied to all IRAC bands at each redshift bin and are different between bands. The discordance between the two apertures results from three factors: (1) flux being missed by the ap2 photometry (shifting the whole distribution up); (2) contamination by neighboring sources (producing the scatter to positive y-axis values); (3) and bright nearby sources affecting the background measurement, which produces a flux underestimate at large apertures (producing the scatter to negative y-axis
values). The correction aims at compensating for missing flux (1), while being independent of artifacts (2 and 3). Only sources with mag_{ap2} < 21 AB are considered, so that the correction value is unaffected by the large scatter at fainter magnitudes. It is clear that the lower the redshift is, the larger is the correction.

We finally infer that the AGN sample is not corrected for this effect, because the emission from AGN sources is assumed to come from the nuclear region, thus not being affected by aperture photometry. Star formation in the host galaxy could, in principle, still produce such bias. However, we do not observe strong evidence for such a scenario in our IR-selected AGN sample (see Section 6).

5. ESTIMATING HOT-DUST AND PAH LUMINOSITIES

In Section 2.2, we mentioned the two rest-frame bands where hot-dust and PAH emission is expected: 3.3 and 4.2 μm. However, at these wavelengths, it is important to take into account stellar emission. Figure 6 shows the estimated 1.6 μm luminosities versus the observed—hence including stellar and non-stellar emission—3.3 μm (left plot) and 4.2 μm (right plot) luminosities for each galaxy population considered in this study. The observe fluxes include stellar and non-stellar emission. The regions between the dotted lines represent the locus at which the SEDs dominated by stellar emission alone are expected to fall (see below). The elliptical data “cloud” tends to fall in this “stellar region.” Any deviation from this region—clear in starburst and AGN populations—is assigned to non-stellar emission (hot-dust and PAH). This is the emission excess that we aim to extract.

To disentangle stellar from non-stellar emission, we first estimate the stellar emission at 3.3 and 4.2 μm for each galaxy. We achieve this estimation in two steps. First, we consider a reference wavelength where the observed flux is expected...
to come entirely from stellar emission. Using this reference wavelength, we then estimate the stellar emission at 3.3 and 4.2 μm. The remaining flux is thus assumed to be due to contribution from non-stellar emission alone.

The reference wavelength used to estimate the stellar emission is the stellar bump at rest-frame 1.6 μm (H-band). This emission bump is observed frequently in galaxy SEDs (Figure 7), being indicative of pure stellar contribution, because at ⩽2 μm, no significant dust emission is expected. This is because UV/optical (stellar or AGN) emission is not enough to heat dust at the level for its cooling emission to dominate at such short wavelengths, or because any dust particle or PAH molecule in a strong radiation field is dissociated. Hence, at wavelengths below ~2 μm, we expect only emission from the Wien tail of the spectrum from the hottest dust grains (e.g., around thermally pulsating AGB (TP-AGB), stars or in a dust torus around an AGN) and from scattered AGN light. Such emission can still be significant enough at 1.6 μm to induce a systematic overestimate of the stellar emission and consequently underestimate the non-stellar contribution. At this stage, we avoid quantifying such bias either for individual galaxies or for the statistically large sample used here.

The flux at rest-frame 1.6 μm is obtained through interpolation between the two wavebands that straddle this rest-frame wavelength at the source’s redshift. However, interpolation is likely to underestimate the true rest-frame 1.6 μm flux value, depending on the source redshift and SED shape. This is evident from Figure 8, in which discrepancies between estimated and true value (always below the 20% level) are shown for typical early-type (red) and late-type (green) galaxies, blue starbursts (blue), and AGN hosts (magenta). These trends were used to correct the interpolated 1.6 μm flux value for each galaxy at its respective redshift. Because of the absence of the H-band from the 109 catalogue, at z ~ 0, the ratio in Figure 8 is <1, because J and Ks passbands were used to interpolate the 1.6 μm flux. The final corrected values are the ones shown in Figure 6.

With the estimated stellar flux at 1.6 μm, we obtain the corresponding stellar contribution at 3.3 and 4.2 μm. This is done with a pure stellar model (solid line in Figure 7; corresponding to a 2 Gyr old elliptical from Polletta et al. 2007), the same used in Figure 6 to compute the stellar-dominated locus. The conversion from 1.6 μm stellar flux to that at 3.3 and 4.2 μm is dependent slightly on redshift, because the considered filters will probe slightly different rest-frame wavelength ranges. Hence, using the pure stellar model (Figure 7), a conversion table was generated by convolving that stellar model with the NIR filters (from J-band to 8 μm) at redshift steps of Δz = 0.01.

We consider the underlying shape of the galaxy SED at 1.6–4.2 μm, because of stellar emission alone, to be common to all galaxy populations referred in this study. This assumption is fair for a universal initial mass function. The stellar emission in this spectral regime originates in cold stars, which live longer, thus producing a constant SED shape over a wide range of ages. Such assumption might be affected by strong differential obscuration affecting the rest-frames 1.6 μm and 3.3 or 4.2 μm. However, this will occur only in extremely obscured systems (e.g., da Cunha et al. 2008), which are rare. Figure 7 supports this assumption, showing how similar the 1.6–4.2 μm stellar SED is between a 13 Gyr old elliptical and a 0.05 Gyr old starburst (models from 109).

The next step is to separate the hot-dust emission from the PAH emission at 3.3 μm. To perform this separation, we use the results from da Cunha et al. (2008), who found that a gray-body model with a temperature of 850 K and a dust emissivity index of 1 is optimal to fit galaxiess’ continuum emission in the 3–5 μm spectral range. Assuming this continuum shape, we normalize it to the 4.2 μm dust emission flux to estimate the flux at 3.3 μm. Removing this flux value from the total non-stellar 3.3 μm emission, one can estimate the PAH 3.3 μm emission flux. This procedure is applied only to non-AGN sources, given that da Cunha et al. (2008) considered only non-AGN sources. In the case of AGN, a dominant power-law continuum shape is more likely. Hence, we estimate the 3.3 μm continuum emission...
in AGN through interpolation of the two bands straddling the band-tracing rest-frame 3.3 μm, assuming $f_\nu \propto \nu^\alpha$.

Henceforth, whenever “PAH emission” is mentioned, we refer to the 3.3 μm PAH emission flux estimated by the aforementioned procedure, and whenever “hot-dust emission” is mentioned, we refer to the estimated 4.2 μm non-stellar emission flux assigned to hot-dust emission alone.

6. THE EVOLUTION OF THE DUST-TO-TOTAL AND PAH-TO-TOTAL LUMINOSITY RATIOS

Figure 9 presents the evolution of the average dust-to-total (left-hand side) and PAH-to-total (right-hand side) luminosity ratios. It is clear that the average contribution of hot-dust at 4.2 μm IR-selected AGN remains constant, with redshift around the 80% level. This constancy results from using IR AGN selection criteria alone. The goal is to independently trace different dust-heating mechanisms (AGN activity versus star formation). Note also the extremely low PAH contribution in AGN, consistent with PAH annihilation by the AGN radiation or emission dilution in the bright AGN-dominated SED. The increase at the lowest redshift interval for the AGN population might be explained by the aperture photometry adopted to estimate colors. With decreasing redshift, a fixed aperture will probe more nuclear regions, enabling the detection of lower luminosity AGN. Being less powerful, these AGN allow for the existence of PAH molecules as opposed to more luminous AGNs, the dominant population with increasing redshifts, which are color-coded: total (black), early-type galaxies (red), late-type galaxies (green), starburst galaxies (blue), and AGN hosts (magenta). Figure 10 (bottom panel in left plot) shows that higher redshift galaxies are dustier in the luminosity range where all samples are complete. However, below the luminosity completeness cuts (Section 2.3), one cannot assess the trends for the high z intervals. The decrease in the number of galaxies showing no dust emission ($L_{dust} = 0$) with decreasing 1.6 μm luminosity is likely to be real (top panel in left plot), as the slope of the relation is constant up to the brightest luminosities.

7. DUST LUMINOSITY DENSITY FUNCTIONS

In this section we measure the hot dust and PAH LDFs and their evolution with redshift for different populations of galaxies. Figure 11 compares the populations at different redshift intervals (shown in individual panels). The populations are color-coded: total (black), early-type galaxies (red), late-type galaxies (green), starburst galaxies (blue), and AGN hosts (magenta). Figure 12 shows the evolution with redshift of the LDFs for each population (shown in individual panels). The volume associated with each galaxy is based on the flux limit of the sample and the k-correction, derived from the galaxy’s own SED (as given by the observed multi-wavelength photometry), and obtained through the $1/V_{max}$ method (Schmidt 1968).

The dust LDFs enable us to evaluate how much dust is contributing to the IR radiation at any given luminosity and redshift for each galaxy population. Note that 1.6 μm luminosities can be taken as a proxy to stellar mass, assuming 1.6 μm to be...
dominated by stellar emission. Therefore, one could assume here, as a proxy, the dust contribution as a function of galaxy stellar mass. Also, using a common luminosity discriminator, allows for a direct comparison between the dust and PAH LDFs.

Although AGN hosts are rare (<4% in our sample), this population clearly dominates the bright-end of the dust LDFs at least at $z > 0.52$. The opposite is seen in the PAH LDFs, in which the AGN population is the weakest contributor at all redshifts.

Figure 12 shows evidence for a number-density evolution in dust LDFs for AGN. If one assumes the dust-to-total luminosity ratio to be constant in IR-selected AGN (Figure 9), then one would not expect to see any evolution with redshift at fixed luminosities in the dust luminosity density ($\rho_D$) assuming a constant number density. However, this seems to be the case, especially from $0.52 < z < 0.94$ to $0.21 < z < 0.52$. Further confirmation of this result might be accomplished by extending this study to deep IRAC coverages available, for example, in the GOODS fields.

As shown in Figure 12, the major evolution in $\rho_D$ and PAH luminosity density ($\rho_{PAH}$) for the non-AGN populations appears mainly at the highest luminosities. That is, the most massive galaxies present the strongest evolution with redshift in $\rho_D$ and $\rho_{PAH}$.

Regarding the PAH LDFs in Figure 11, the faint end is always dominated by the starburst population, followed by the late-type galaxies, and then the early-type galaxies. At high luminosities, the three non-AGN populations seem to contribute at comparable rates. That relative contribution, however, does not happen in the dust LDFs, in which the early-type population is the weakest contributor, whereas late-type and starburst populations have the highest contribution. This behavior is explained in Figure 9, which shows that the higher the redshift is, the larger is the difference in dust-to-total luminosity ratio between the early-type galaxies and late-type or starburst galaxies, although this is not the case for the PAH-to-total luminosity ratios.

The reason why this happens is not straightforward, but assuming the graybody model scaling should instead more or less correlate to 3.3-PAH strength, one can conclude the following scenarios: (1) extra flux in early-type galaxies at 3.3 $\mu$m unaccounted by PAH emission; (2) or extra emission at 4.2 $\mu$m in starburst and late-type galaxies. The former could imply higher gray-body temperatures (>850 K) in early-type galaxies, for example, induced by low-luminosity AGN, which were missed by the adopted AGN selection, while (2) could be explained by Mentuch et al. (2009), who showed evidence for extra emission in the 2–5 $\mu$m spectral range unaccounted by the same gray-body model we assume plus PAH emission. They also found that this extra emission correlates with star formation (Mentuch et al. 2009, 2010), thus explaining why we observe the enhancement in starburst and late-type—but not in early-type—galaxies. This reasoning also implies that the extra-emission heating mechanisms are, in part, different from those of the 3.3-PAH feature. One source of extra emission at $\sim$4.2 could be the Br$\alpha$ emission line (4.05 $\mu$m). If present, it would imply an underestimate of the 3.3-PAH flux. However, the star-forming sample gathered by Yamada et al. (2013) shows...
Figure 12. Comparing the hot-dust (left plot) and PAH (right plot) LDFs for each galaxy population between redshift bins. Line coding as in Figure 10. Intervals are not plotted whenever more than 30% of the sources had no $V_{\text{max}}$ estimate.

Figure 13. Evolution with redshift of the dust and PAH luminosity densities (left and right plots, respectively) depending on galaxy type (color coding as in Figure 6). Transparent regions show the associated 1σ error. Empty regions show the results if a correction for incompleteness is attempted (only for the total and non-AGN populations). The redshift intervals are indicated at the bottom as horizontal error bars. The gray shaded region in the left plot refers to the evolution trend of the cold-dust luminosity density alone derived from FIR observations (Magnelli et al. 2009; Chary & Pope 2010) and it is scaled to the $\rho_D$ value of the total population at $0.52 < z < 0.94$. For improved visual comparison, the y-axis scale was matched between the two plots. However, this means $\rho_{\text{PAH}}$ estimates for the AGN population fall mostly out of the plot.

That the luminosity ratio between $Br_{\alpha}$ and $3.3$-PAH feature is $L_{\text{Br}_{\alpha}}/L_{3.3} = 0.08 \pm 0.04$, which is not enough to account for the difference pointed out in Figure 11.

8. EVOLUTION OF DUST LUMINOSITY DENSITY

In Figure 13, we present the evolution of $\rho_D$ and $\rho_{\text{PAH}}$ since $z \sim 1$ (left and right plots, respectively). We also compare $\rho_D$ to the cold-dust luminosity density estimated from FIR observations (70–500 μm, dark gray shaded region; Magnelli et al. 2009; Chary & Pope 2010), linearly translated to obscured star formation. However, comparing the luminosity density at present time to that at $0.52 < z < 0.94$, the drop in $\rho_D$ is more significant than that of the cold-dust luminosity density, by $\sim 0.5$ dex.

Such decrease is driven mostly by the non-starburst populations. Although one might attribute part of the decay to the strong evolution shown by AGN hosts (see also Hanami et al. 2012), whose FIR SED is related to star formation and not to AGN activity, the late-type population also plays a role in shaping such difference between hot and cold $\rho_D$ evolution. However, even the starburst population shows a different rate of evolution compared with that of the FIR evolution: the drop in $\rho_D$ is still greater by $\sim 0.3$ dex compared with that of cold-dust.

The faint population, gradually missed with increasing redshifts by our completeness cuts, is likely a significant contributor to the overall $\rho_D$ and $\rho_{\text{PAH}}$ given the higher hot-dust and PAH contribution observed in their SEDs (Figure 10). This implies that the discrepancy between the hot and cold dust regimes is likely larger. Also, Figure 12 shows a slower evolution in $\rho_D$ and $\rho_{\text{PAH}}$ at fainter luminosities. Accepting this as true, one can then consider the faint end shape of the LDFs (i.e., that below the completeness cut) is unchanged from a redshift interval to a subsequent lower one and estimate a completeness correction. This is shown in Figure 14 for the total and starburst populations. Integrating a given LDF at luminosities fainter than the completeness cut will thus provide an estimate of the extra $\rho$ missed by our sample. Applying this correction yields extra luminosity density represented as the empty regions shown in Figure 13 (only for the total and non-AGN populations). These corrections are expected to provide upper limits for the $\rho$ values.

Recent work on the 3.3 μm PAH feature with Spitzer and Akari out to $z \sim 2$ does not show an evolution with redshift of the luminosity ratio $L_{3.3}/L_{8–1000}$μm (Magnelli et al. 2008; Dasyra et al. 2009; Sajina et al. 2009; Siana et al. 2009; Imanishi et al. 2010; Yamada et al. 2013). However, comparing with hot-dust, our study seems to support slight variation of the hot-dust-to-PAH luminosity ratio with redshift.
The values are approximated to unit. Note.

Figure 14. Extending the dust (left-hand side panels) and PAH (right panels) LDFs below the completeness cut (indicated with a gray square) assuming a similar shape as that observed for lower redshift intervals. Only LDFs for the total (upper panels) and starburst (lower panels) populations are displayed. Line coding as in Figure 10.

Table 3 shows, for each redshift interval, the contributions of each of the galaxy populations to the overall dust luminosity density at rest-frames 3.3 and 4.2 μm. These values refer to contributions down to the adopted luminosity completeness cut.

9. CONCLUSIONS

In this work, we used observations tracing rest-frame 4.2 μm to explore the properties of hot-dust (∼690 K) emission. This wavelength is used also to infer the dust contribution at rest-frame 3.3 μm and to help assess 3.3-PAH strength. Our approach considers stellar, dust, and PAH emissions separately, as well as the separation of the IR galaxy population into early-type, late-type, starburst, and IR-selected AGN. This method allows the evaluation of the IR luminosity functions depending on galaxy type and distance, as well as to estimate how much dust contributes to the IR emission. We conclude the following.

1. Evolution with redshift of the hot-dust luminosity densities resembles that of cold-dust, but it drops more steeply (at least 0.5 dex more) with decreasing redshift. The discrepancy is larger if one attempts to correct for sample incompleteness. The reason for the discrepancy is probably a combination of the following: with decreasing redshift, the star formation becomes gradually unable to heat dust to such high temperatures for it to contribute significantly to the galaxy SED at such short wavelengths; dust is located gradually at increasingly larger distances from the heating sources (stars or active nuclei); and distinct evolution of different heating mechanisms at play in AGN hosts. This trend supports the scenario in which galaxy obscuration increases with redshift, as proposed in the literature (Section 8).

2. Whereas the average dust-to–total luminosity ratio is observed to increase with redshift, the average PAH-to–total luminosity ratio is consistent with being constant. The hot-dust-to–PAH luminosity ratio also depends on galaxy spectral type. A plausible explanation might be related to the findings of Mentuch et al. (2009), who observed increased extra emission at 2–5 μm with increasing star-formation rates (Section 7).

3. Hot-dust and PAH LDFs of the non-AGN populations show that the hot-dust and PAH emission in the most luminous galaxies at 1.6 μm (i.e., the most massive) decreases faster (with decreasing redshift) than in less luminous galaxies (Section 7).

4. Down to our luminosity limit, the AGN population comprises only <3% of the total galaxy population at z < 0.94, but its contribution to the overall hot-dust luminosity density increases from 3% at 0.05 < z < 0.19 to 33% at 0.52 < z < 0.94, and it clearly dominates the bright end of the total hot-dust LDFs at 0.52 < z < 0.94 (Section 7). The main driver for this is the high dust-to-total luminosity ratio at rest-frame 4.2 μm found in IR-selected AGN: ∼0.8 (Section 6).

5. At M_{1.6} > −25, there is an increase of the dust-to–total luminosity and PAH-to–total luminosity ratios with decreasing luminosity, but deeper data might be required to confirm this result (Section 6).

The authors thank the COSMOS team for providing the photometric and redshift catalogs which make the base of this work. H.M. acknowledges the support from Fundação para a Ciência e a Tecnologia through the scholarship SFRH/BD/31338/2006.
and CONICYT-ALMA by the postdoctoral scholarship under the project 31100008. H.M. and J.A. acknowledge support from Fundação para a Ciência e a Tecnologia through the projects PTDC/CTE-AST/105287/2008, PEst-OE/FIS/UI2751/2011 and PTDC/FIS-AST/2194/2012. H.M. acknowledges the support by UCR while visiting Dr. Bahram Mobasher as a visitor scholar. H.M. acknowledges the frequent use of C, Topcat, Supermongo, and Python.

**APPENDIX**

**PHOTOMETRIC REDSHIFTS FOR IR-SELECTED AGN**

The photometric redshift ($z_{\text{phot}}$) analysis adopted in this work (and done in I09) is based on 0.15–8 μm photometry. However, AGN activity might induce emission in this spectral regime, thus affecting the analysis (Rowan-Robinson et al. 2008, S11). Here, we test the $z_{\text{phot}}$ quality obtained for sources in our IR-selected AGN sample.

For the purpose of quality check we adopt the normalized median absolute deviation (N MAD; by definition $\sigma_{\text{N MAD}} = 1.48 \times \text{median}(|z_{\text{spec}} - z_{\text{phot}}|/(1 + z_{\text{spec}}))$, Hoaglin et al. 1983), which, for a Gaussian distribution, is directly comparable to the $\sigma_{\chi^2/2}$ value quoted in other papers. Also, the fraction of outliers (sources with $|z_{\text{spec}} - z_{\text{phot}}|/(1 + z_{\text{spec}}) > 0.15$) is denoted by $\eta$. The subsequent discussion considers only sources with $i^* < 25$ AB.

Among the IR AGN sample, there are 605 sources with good quality spectra. Comparing the estimated spectroscopic redshifts with the photometric redshifts estimated by I09 ($z_{\text{I09}}$), the quality achieved is $\sigma_{\text{N MAD}} = 0.123$, with $\eta = 39\%$.

Ilbert et al. also computed in parallel the best-fit solution using AGN-like templates (those considered by S11). If one adopts these estimates instead (z_{\text{AGN}}), the quality is improved to $\sigma_{\text{N MAD}} = 0.036$ and $\eta = 23\%$. This result is similar to what is achieved when applying the Salvato et al. (2009) method to Chandra-detected sources, even though they are plagued by a higher fraction of outliers. One can further improve these results by adopting $z_{\text{I09}}$ or $z_{\text{AGN}}$ solutions, depending on which presents the lowest $\chi^2$ value. This procedure assigns the $z_{\text{AGN}}$ solution to 66% of the KI-selected sample with spectra and reduces the $\sigma_{\text{N MAD}}$ and $\eta$ values to 0.021 and 18%.

Figure 15 compares directly $z_{\text{I09}}$ and $z_{\text{AGN}}$ solutions for IR-selected AGN sources. One can identify three regions in the plots where the two model sets provide distinct solutions: (a) sources with $z_{\text{I09}} > 1$ and $z_{\text{AGN}} < 0.5$; (b) sources with $z_{\text{I09}} > 2$ and $0.5 < z_{\text{AGN}} < 1.5$; (c) sources with $0.8 < z_{\text{I09}} < 1.8$ and $z_{\text{AGN}} > 1.8$. In these regions, AGN and I09 solutions present, on average, $\chi^2 \sim 1$ (meaning both provide a good fit to the observed data); hence, the $\chi^2$ check referred to earlier is irregular in these specific samples.

In region A, there are 18 sources with spectroscopy; all but 3 fall at $z_{\text{spec}} < 1$ (only one at $z_{\text{spec}} < 0.5$). The X-ray detection rate (58 sources among 1724) is low for a $z < 0.5$ AGN population but acceptable for a higher redshift population, including AGN and non-AGN sources. Not only the XMM-Newton and Chandra coverages gradually miss more AGN sources with increasing redshift, but the reader should also be reminded that KI AGN-selection is contaminated by non-AGN sources at $z > 2.5$, where 63% of the A sample likely falls (considering the photometric redshifts from I09). Considering S11 redshift estimates ($z_{\text{S11}}$) for the 58 X-ray–detected sources, only 2 of them fall at $z < 1$. These results support the scenario in which sample A is composed mostly by $z > 1$ sources, and we thus assign the photometric redshifts from I09 to sources in sample A. We note, however, that 37 of these sources (64%) require AGN-like templates (S11). The difference between $z_{\text{S11}}$ and $z_{\text{AGN}}$ is likely not just due to variability (about 30% of those sources are non-variable, i.e., variability below 0.25; S11), but rather it is a result from not considering luminosity priors (as used in S11) when computing $z_{\text{AGN}}$.

In sample B (selected as sources with $z_{\text{AGN}} > 0.5$, $z_{\text{I09}} > z_{\text{AGN}}$, and $|z_{\text{I09}} - z_{\text{AGN}}|/(1 + z_{\text{AGN}}) > 0.2$), we do not find such a clear trend; spectroscopic measurements and $z_{\text{S11}}$ estimates show equal evidence for a sample composed by sources at $z < 1.5$ and $z > 1.5$. The upper histogram in Figure 15 shows the redshift uncertainty distribution by comparing $z_{\text{I09}}$ and $z_{\text{AGN}}$ to $z_{\text{S11}}$ for sample B (where $z_{\text{I09}} > z_{\text{AGN}}$). The peak of the $z_{\text{AGN}}$ distribution at zero is dominated by sources that already show $\chi^2_{\text{AGN}} < \chi^2_{\text{I09}}$. Hence, we do not modify the assigned photometric redshifts resulting from the comparison between $\chi^2$ values.

Sources found in region C (selected as $z_{\text{AGN}} > 0.5$, $z_{\text{AGN}} > z_{\text{I09}}$, and $|z_{\text{I09}} - z_{\text{AGN}}|/(1 + z_{\text{AGN}}) > 0.1$) mostly support the
The Astrophysical Journal, 776:117 (12pp), 2013 October 20

The lower histogram in Figure 15 is dominated by sources with $z_{\text{AGN}}$ solution for sources with $z_{\text{spec}}$, and red circles consider a mixture between $z_{\text{phot}}$ estimates resulting from either AGN model fit or non-AGN (I09) model fit. (A color version of this figure is available in the online journal.)

$z_{\text{AGN}}$ solution. The peak in the uncertainty distribution in the lower histogram in Figure 15 is dominated by sources with $\chi^2_{\text{AGN}} / \chi^2_{\text{IR}} > 0.7$, whereas sources with a $z_{\text{AGN}}$ uncertainty of $\sim-0.4$ have mostly $\chi^2_{\text{IR}} / \chi^2_{\text{AGN}} < 0.7$, and the $z_{\text{IR}}$ uncertainty is around zero. The remaining sources with large $z_{\text{AGN}}$ uncertainties have $z_{\text{S11}}$ estimates, and most show variability.

Hence, for the IR-selected AGN sample, we adopt the $z_{\text{AGN}}$ solution for sources with $z_{\text{AGN}} > 0.5$ and $z_{\text{AGN}} > z_{\text{IR}}$ and $\chi^2_{\text{AGN}} / \chi^2_{\text{IR}} > 0.7$; or $z_{\text{AGN}} < z_{\text{IR}}$ and $\chi^2_{\text{IR}} / \chi^2_{\text{AGN}} > 1$. The remainder of the population is assigned the $z_{\text{IR}}$ solution. The photometric redshift quality achieved for the IR-selected AGN sample when compared with spectroscopic estimates is $\sigma_{\text{IR}} = 0.020$ and $\eta = 15\%$ (Figure 16). These $z_{\text{phot}}$ estimates become obsolete when a higher-priority redshift estimate is available (such as spectroscopic or S11 $z_{\text{phot}}$ estimates; see Section 3). For example, by assuming the S11 $z_{\text{phot}}$ estimates, which take into account luminosity prior and the effect of variability, the photometric redshift quality is improved to $\sigma_{\text{S11}} = 0.015$ and $\eta = 10\%$.

REFERENCES

Barlow, M., Krause, O., Swinyard, B. M., et al. 2010, A&A, 518, 138
Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 1999, MNRAS, 302, 632
Bouwens, R. J., Illingworth, G. D., Franx, M., et al. 2009, ApJ, 705, 936
Brusa, M., Civano, F., Comastri, A., et al. 2010, ApJ, 716, 348

Figure 16. Testing the match between spectroscopic ($x$-axis) and photometric ($y$-axis) redshift estimates. Black triangles consider only the $z_{\text{phot}}$ estimates from I09, and red circles consider a mixture between $z_{\text{phot}}$ estimates resulting from either AGN model fit or non-AGN (I09) model fit.