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Dust in the High Redshift Universe

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Abstract. This paper reviews the dust content of the high redshift ($z > 2$) universe. Studies of the various "species" in the high-z "zoo" show that almost all have strong evidence for containing dust. The one exception, where the evidence is not yet convincing, is in quasar absorption line systems, particularly those with low column density. These may not even be associated with galaxies. The high-z galaxy types which do show evidence for dust are all strongly star forming. Hence, as seen locally, star formation and dust in the distant universe are also strongly correlated. It is beyond debate that star formation at $z \sim 3$ is dominated by dusty systems who emit most of their bolometric flux in the rest-frame FIR. What is not clear is whether these systems are totally invisible at shorter wavelengths, or whether a large fraction are visible in the rest-frame UV as Lyman Break Galaxies. The issue may not be settled until the sub-mm background is definitively resolved.

1. Introduction

Here I review some of the things we know about dust in the high redshift ($z \gtrsim 2$) universe. This review is meant to be an introduction to the literature. While by necessity incomplete, it is my hope that the reader will get an appreciation for some of the activity of the field and the researchers involved.

To many extraglactic astronomers and cosmologists dust is at best a nuisance. However, it is fairly ubiquitous and perilous to ignore. For example, Blakeslee et al. (2003), following on from Aguirre (1999) and Goobar et al. (2002), show that the distinctive signature of cosmological acceleration in the differential Hubble diagram can also be mimicked with a model containing gray dust having fixed spatial density in the intergalactic medium (IGM). While there are a variety of reasons to believe that the effects are not significant (e.g. Aguirre & Haimann 2000; Paerels et al. 2002; also cf. §2.4 below), it is too early to totally rule out the gray dust model.

As in the local universe, dust is highly correlated with star formation. Since all studies show that the co-moving star formation rate density (SFRD) monotonically increases with z out to a redshift of at least 1 (e.g. Madau et al. 1996) we expect that dust may be increasingly important at higher redshift (Calzetti & Heckman 1999). Dust is especially important in interpreting the cosmic star formation history as shown in so called "Madau Plots" of SFRD(z). In some early studies dust was ignored leading to a view that SFRD(z) peaked around

$z \sim 1$ and declined towards higher redshift (e.g. Madau et al. 1996). It is now recognized that most of the UV emission from high-z star formation is at least somewhat obscured by dust (e.g. Madau, Pozzetti, & Dickinson 1998; Pettini et al. 1998) leading to SFRD(z) plots that flatten for $z \gtrsim 1$ (e.g. Calzetti 1999).

Since observations of high-z star forming galaxies are somewhat easier in the rest-frame UV than in the rest-frame far-infrared (FIR), it is of interest to know if star formation rates can be recovered from rest-frame UV observations through suitable application of reddening laws. More importantly we must ask whether the numerous high-redshift galaxies detected in the rest frame UV are really significant in terms of the total star formation happening in the early universe.

This review is broken into two main sections. § 2 reviews dust content of the species in the "high-z zoo". § 3 reviews the evidence for galaxy scale reddening laws working at $z > 2$ and considers the debate as to whether the majority of star formation is totally hidden from the rest-frame UV and optical at high redshift. § 4 briefly summarizes breaking news and the expected progress in the field.

2. Evidence for High Redshift Dust

High-redshift objects can be selected by many ways at a variety of wavelengths. While there is some overlap in the properties of the galaxies selected by the different techniques they typically go by different names in the literature. Table 1 summarizes the beasts in the high-z zoo.

Table 1. The high-z zoo

wavelength observed	rest	name
optical	UV	High-z quasars Lyman Break Galaxies (LBG) Lyman-α galaxies Quasar absorption line systems
NIR	optical	Extremely Red Objects (ERO)
sub-mm/mm	FIR	Sub-mm and mm galaxies, SCUBA galaxies
radio	radio	Micro-Jansky Radio Sources

2.1. High-z quasars. Due to their high-luminosities, quasars are relatively easy to detect out to the highest known redshifts (e.g. Irwin & McMahon, 1991; Fan et al. 2001; 2003). The current record holder has $z = 6.43$ (Fan et al.2003). One of the most early and direct measurements of high-z dust came from Omont et al. (1996) who observed the $z = 4.7$ radio quiet quasar BR1202-0725 with the IRAM array. They simultaneously detected both mm wavelength dust continuum emission as well as molecular CO (5-4) and (7-6) lines in emission. The mm observations show two sources: the quasar and a companion galaxy. The dust emission of the latter is certainly powered by star-formation. So in this system we see star-formation and it's key ingredients, dust and molecular gas.

2.2. Lyman Break Galaxies. Lyman Break Galaxies are selected using broad band filters in the optical and/or NIR. The strong spectral break at $\lambda = 912$Å, due to the ionization of hydrogen, is readily seen in broad-band SEDs. For example, galaxies with $z \sim 2.8$ will have no flux in the HST/WFPC2 F300W (U) band but can be detected at longer wavelengths, hence the term U-dropout (or B-dropout, V-dropout, etc.). LBGs are typically selected for having a very red color (or color limit) using filters that straddle the break, but relatively blue color using filters that are longwards of the Lyman break (e.g. Madau et al. 1996; Steidel et al. 2003). This ensures the selection of star forming galaxies, and selects against very old or very dust reddened galaxies. The ability to obtain optical photometry to the 25th magnitude and beyond with current technology means that LBGs are the most abundant species in the High-z zoo (Adelberger & Steidel 2000, hereafter AS00).

LBGs display a remarkable similarity to nearby UV bright starburst galaxies as defined by the IUE atlas of Kinney et al. (1993). Both types have rest-frame SEDs that are at the blue end of those found for normal galaxies (Papovich et al. 2001); strong emission lines in the rest-frame optical (Pettini et al. 1998); rest-frame UV spectra dominated by high ionization wind lines as well as strong narrow interstellar absorption lines (Tremonti et al. 2001; Shapley et al. 2003); and a net blue shift of the interstellar absorption lines with respect to photospheric stellar lines, indicative of strong outflows in the ISM (Pettini et al. 2000; Shapley et al. 2003). The main difference is that LBGs are much more luminous (e.g. AS00), typically by an order of magnitude or more even without any dust corrections. Since the two types have similar high effective surface brightnesses (Meurer et al. 1997), LBGs are also much larger, typically having effective radii of a few kpc (Giavalisco et al. 1996). In short, LBGs look like local UV bright starbursts but scaled up in size and hence luminosity.

While we know a lot about the dust content of the local UV bright starburst population (e.g. Calzetti et al. 1994; 2000; Calzetti 2001; Meurer et al. 1995; Gordon, Calzetti & Witt 1997; Meurer et al. 1999, hereafter MHC99), much less is known directly about the dust content of LBGs. Most individual LBGs are not detected in the sub-mm with the Submillimeter Common User Bolometer Array (SCUBA), although there are a few rare exceptions (AS00, Baker et al. 2001). Stacked SCUBA studies also have had mixed success in detecting LBGs (AS00; Chapman et al. 2000; Peacock et al. 2000). Nevertheless, we can infer the presence of dust in LBGs via reddening: we know that they have a strong ionizing population from their emission line spectrum, yet their colors are not as blue as expected from un-reddened stellar populations. Using broad-band SEDs Papovich et al. (2001) estimate the reddening distribution of LBGs which peaks at $E(B-V) \approx 0.15$. A variety of studies starting with Meurer et al. (1997) have estimated typical UV attenuations in LBG samples using just rest-frame UV colors. Most recent studies estimate UV attenuation factors around 5 using this method. One of the most recent works in this vein is Vijh, Witt & Gordon (2003) who also present a nice compilation of attenuation estimates for LBGs. This subject is addressed in more detail in §3.

2.3. Lyman-α galaxies. Initially Lyα emission was thought to be one of the best ways to detect the first epoch of galaxy formation (Partridge & Peebles 1967). However, after many disappointing surveys it was realized that there was something wrong with the original predictions (e.g. Pritchet 1994). Spectroscopic follow-up of LBGs showed that they have low rest-frame Lyα equivalent widths ($\lesssim 20$Å) and fluxes lower than expected for their UV continuum strength (e.g. Steidel et al. 1996a,b; Lowenthal et al. 1997). This is due to the effects of resonant scattering of the Lyα photons through the ISM of the galaxies, which greatly increases the total path required for the photons to escape the system. Hence even a small amount of dust is enough to greatly attenuate Lyα emission compared to the neighboring continuum. In an expanding dusty ISM, such as a galactic wind, Lyα photons can escape by back scattering out the far-side of the outflow resulting in a distinctly asymmetric line profile characterized by a sharp blue side cutoff. Such Lyα profiles are indeed observed in both nearby starbursts (Kunth et al. 1998) as well as LBGs (Shapley et al. 2003).

Recent high-z Lyα surveyors have learned their lessons and are going deeper and wider, and hence are becoming more successful (e.g. Rhoads et al. 2000). In fact the current most distant "normal" galaxies ($z \sim 6.5$) have been found using narrow band imaging targeting Lyα (Kodaira et al. 2003). Spectroscopic confirmation of these and other blank-field Lyα emitters inevitably shows the asymmetric profiles indicating the presence of a dusty expanding ISM (Kodaira et al. 2003; Rhoads et al. 2000; 2003).

2.4. Quasar Absorption Line Systems. The absorption lines in the spectra of quasars probe the gas phase of intervening systems, which need not necessarily be galaxies (self-gravitating conglomerations of stars, gas and dark matter). The most commonly observed feature seen is Lyα absorption. In the literature, Lyα absorption lines are referred to (in order of decreasing $\log(N_{\rm HI})$) as "damped Lyα absorption systems" (DLAS) with $\log(N_{\rm HI}[{\rm atoms\,cm^{-2}}]) \gtrsim 20$, "Lyman limit systems" with $17 \gtrsim \log(N_{\rm HI}) \gtrsim 20$, and "Lyman forest" clouds $14 \gtrsim \log(N_{\rm HI}) \gtrsim 17$.

Metal absorption lines are also seen, albeit much less frequently. These include C, Si, Mg, S, Zn. Metals are also seen in the IGM out to $z \sim 5$, with little evolution in the cosmic density in C IV absorption for $1.5 \lesssim z \lesssim 5.5$ (Songaila 2001; Pettini et al. 2003). This lack of evolution is somewhat puzzling. It may indicate a massive pollution event to the IGM at $z > 5.5$ (Songaila 2001), or alternatively may be due to IGM features being correlated with star formation which also evolves only weakly with redshift (Adelberger et al. 2003).

It is less clear that the IGM contains significant quantities of dust. We expect a bias against detecting dusty IGM clouds in optically selected quasar samples - the dust would diminish the flux of the background quasar (Fall & Pei, 1993). However, a study of a radio selected sample of quasars shows that the dust bias is at most a factor of two in absorption line systems having $2 \lesssim z \lesssim 3$ (Ellingson et al. 2001). Prochaska et al. (2003) provide some evidence suggestive of dust in a DLAS at $z = 2.6$: the elemental abundance pattern of this system scales well to the solar abundance *after correction for depletion onto dust grains.* This on its own is not convincing proof of dust in DLASs, nor does it follow that lower column density sight lines of the IGM contain dust.

2.5. Extremely Red Objects. Elston et al. (1988) pointed out the existence of an interesting new population of galaxies having very red optical - NIR colors, $R-K \gtrsim 5$. These "Extremely Red Objects" have cropped up in numerous other deep NIR surveys although the exact selection limits vary. Detailed studies of the multi-wavelength SEDs of EROs show that they are a mixed bag, with roughly half being dusty starbursts and the other half being passively evolving (presumably dust-free) ellipticals at $z \sim 1$ (e.g. Smail et al. 2002a). Likewise, Ivison et al. (2002) find that about half of the radio-confirmed bright SCUBA sources have ERO or very red counterparts showing the strong overlap between the SCUBA and ERO populations.

By selecting purely in the NIR it is possible to select the most extreme galaxies - the Hyper Extremely Red Objects or HEROs (Totani et al. 2001) with colors $J-K \gtrsim 3$ so red that they can not be produced by pure passive evolution - some dust is required. Totani et al. find that the these are best modeled as very dusty starbursts at $z \sim 3$.

2.6. Sub-mm/mm Galaxies. The advent of SCUBA on the 15m James Clerk Maxwell Telescope made it possible to survey for dust emission from high-luminosity, high-z galaxies. SCUBA has been particularly effective at 850μm, where "negative K-corrections" result in sources with fixed star formation rate having nearly constant flux as a function of z in the range of ~ 0.5 to 5 (Guiderdoni et al. 1997). The 850μm confusion limit for SCUBA is $\sim$2 mJy (Hughes et al. 1998) corresponding to Bolometric luminosities of $\sim 2\times10^{12}\,L_\odot$, about that of Arp 220. Hence only ultra-luminous ($L_{\rm bol} > 10^{12}\,L_\odot$) and hyper-luminous galaxies ($L_{\rm bol} > 10^{13}\,L_\odot$) are detectable with SCUBA in blank fields. Similar star formation rate detection levels are also possible at 1.2mm, with using the MAMBO detector on the 30m IRAM telescope (Dannerbauer et al. 2002). Staring at strong lensing clusters allows the detection limit to be pushed down by a typical factor of ~ 3 (Smail et al. 2002b). The resulting lens amplification corrected number counts indicates that the 850μm background is nearly completely resolved at sub-mJy levels.

The large beam sizes of SCUBA ($15''$) and MAMBO ($11''$) make identification of optical counterparts difficult. The optical counterparts are usually faint, and often not the most obvious galaxy in the sub-mm beam; Frayer et al. (2003) show an example of such an identification. Radio synthesis follow-up studies allows the counterparts of sub-mm and mm galaxies to be pinpointed to sub-arcsec accuracy. Ivison et al. (2002) find that 60% of their 850μm "8 mJy sample" have robust radio identifications, and that 90% of those identified in the radio have near-infrared (NIR) and optical counterparts. Hence, over half of the brightest SCUBA sources have rest frame UV and optical counterparts. The success rate for finding optical and NIR counterparts for fainter highly magnified lensed SCUBA sources appears to be lower (Smail et al. 2002b), although the radio detection limits tend not to be that deep in those cases. The high dust luminosity and faint rest-frame UV and optical fluxes indicate that sub-mm/mm galaxies are similar to local Ultra Luminous Infrared Galaxies (ULIRGs; e.g. Goldader et al. 2002), but scaled up in luminosity.

Details and further information on sub-mm galaxies can be found in the excellent and comprehensive review of Blain et al. (2002).

2.7. Micro-Jansky Radio Sources. The radio emission of local star forming galaxies correlates very well with the FIR emission, although the physics behind the correlation is less clear (Helou et al. 1985; de Jong et al. 1985; Lisenfeld et al. 1996). Hence, radio observations are an excellent means to peer through the dust in a galaxy and observe star formation. For sources with very low fluxes, $f_\nu(3.5\text{cm}) \lesssim 35\,\mu\text{Jy}$, the frequency domain spectral slope α ($f_\nu \propto \nu^{\alpha}$') becomes more steep ($\alpha$ -0.7) indicating that star forming galaxies are dominating over AGN (Fomalont et al. 2002). In contrast to the sub-mm, star forming galaxies dim considerably with redshift. Hence, spectroscopic, follow-up studies show that the majority of μJy sources are at redshifts $z < 1.5$. Simulations show that star forming galaxies should not be detectable for $z > 3$ in the deepest radio images currently available without evolution to include sources much more luminous than Arp 220 (Chapman et al. 2002).

The μJy sources with optically faint counterparts ($I \gtrsim 24$) are most likely to have $z > 2$ (Richards et al. 1999; Chapman et al. 2003a). The main evidence for dust in these is their high detectability rate with SCUBA at 850μm (e.g. Barger et al. 2000; Chapman et al. 2003a). In addition, the optical counterparts tend to be redder than other field galaxies with the same I magnitudes and become progressively redder towards fainter magnitudes which also suggests the presence of dust in the host (Chapman et al. 2003a). Unlike the SCUBA galaxies, μJy radio galaxies usually have optical counterparts when one looks hard enough (Richards et al. 1999). Since these are rather faint, redshifts are difficult to obtain in the optical. Redshifts can be crudely estimated using the ratio of SCUBA and radio fluxes (e.g. Carilli & Yun 1999), however there are nasty degeneracies with dust temperature to contend with (Blain 1999).

3. Starburst Reddening and the sub-mm background

Here I summarize the status of a recent debate within the field over the last four or five years: which population of galaxies contributes the most to the total star formation rate density at high redshift? The two top contenders are the optically selected LBG population and the "SCUBA" sub-mm and mm galaxies. Table 2 summarizes some properties of these contenders and their estimated contribution to the sub-mm background $S_{850\mu\text{m}} = 44\,\text{Jy}\,\text{deg}^{-2}$ (Fixsen et al. 1998).

As noted above, LBGs strongly resemble UV bright starbursts. One of the strongest correlations seen in local UV bright starbursts is the so-called IRX-β relationship, shown in Fig. 1 (Meurer et al. 1995; MHC99). This relationship shows that the ratio of dust emission in the FIR to (residual) UV emission (infra-red excess or IRX) correlates with the UV spectral slope β (defined by the spectrum $f_\lambda \propto \lambda^\beta$). Since IRX is basically a measure of dust extinction this means that starburst redden as they become more extincted. The simplest explanation for this correlation is that the dust has a strong diffuse foreground contribution to its distribution, i.e. it behaves like a foreground screen (e.g. Witt & Gordon 2000; MHC99; Calzetti et al. 1994; Witt et al. 1992). Indeed, correcting survey data for dust absorption using simple reddening models greatly improves the consistency of multi-wavelength SFRD(z) plots (Calzetti 1999).

It should be noted that not all local star forming galaxies obey this relationship. While it works well for the UV-bright calibrating sample whose

Table 2. What dominates the SFR at $z \sim 3$?

Property	LBGs	SCUBA galaxies
Detectability	"easy" & numerous ~ 6000 deg^2 to $R \sim 25.5$ (Steidel et al. 2003)	difficult & rare ~ 300 deg^2 to ~ 6.5mJy confusion limited (e.g. Hughes et al. 1998)
Luminosity	$L_{\rm UV} \sim 10^{10-11}\,L_\odot$ (without dust correction)	$L_{\rm FIR} \sim 10^{12-13.5}\,L_\odot$
$L_{\rm FIR}/L_{\rm UV}$ local analog	$\lesssim 100$ (average $5-8$) UV-bright starbursts (MHC99)	$30 - 3000^a$ ULIRGs (Goldader et al. 2002; AS00)
Contribution to S_{850} after corrections	93% $\sim$1.3 completeness $\sim$6 dust absorption (AS00)	100% (by definition...) $\sim$5 completeness Chapman et al. (2000)

[a] One deviant sub-mm galaxy is SMMJ16358+4057 with $L_{\rm FIR}/L_{\rm UV} \sim 10$ (Smail et al. 2003).

members have $L_{\rm bol} \lesssim 10^{11.5}$ it does not work well for ULIRGs which typically have $\log(F_{\rm FIR}/F_{1600}) > 2$ and fall well above the IRX-β relationship (Goldader et al. 2002). A significant fraction ($\sim 30\%$) of normal (i.e. non starburst) galaxies fall below the IRX-β relationship, presumably due to strong contamination from intermediate age populations in the near UV (Seibert, 2003).

Be that as it may, the IRX-β correlation seems to work well for strongly star forming galaxies with modest amounts of dust absorption. While there is some distaste for the foreground screen geometry in the literature (e.g. Charlot & Fall 2000), we need not fixate on the interpretation to use the correlation. We have seen the myriad ways that LBGs resemble local starbursts, so it seems reasonable to suppose that they obey the same IRX-β correlation. If so, then we can estimate the total extinction correction UV flux (and integrated cosmic UV flux density), and hence star formation rate of LBGs from just their rest-frame UV-flux and colors. This was done by MHC99. An even better job, using similar and other methods, was done by AS00. Both papers find that only $12\% - 20\%$ of the UV flux emitted at rest $\lambda \approx 1600$Å reaches the earth (cf. Vijh et al. 2003, and references therein).

It is hard to test whether the IRX-β relation holds for LBGs, since the predicted sub-mm fluxes are below the SCUBA confusion limit (MHC99). AS00 show that there are a few individual LBGs that have been directly detected with SCUBA and these largely obey the IRX-β relation. One lensed LBG, MS1512+36-cB58, falls somewhat below the IRX-β relationship, albeit with large error bars (Baker et al. 2001). If a large fraction of LBGs have similar

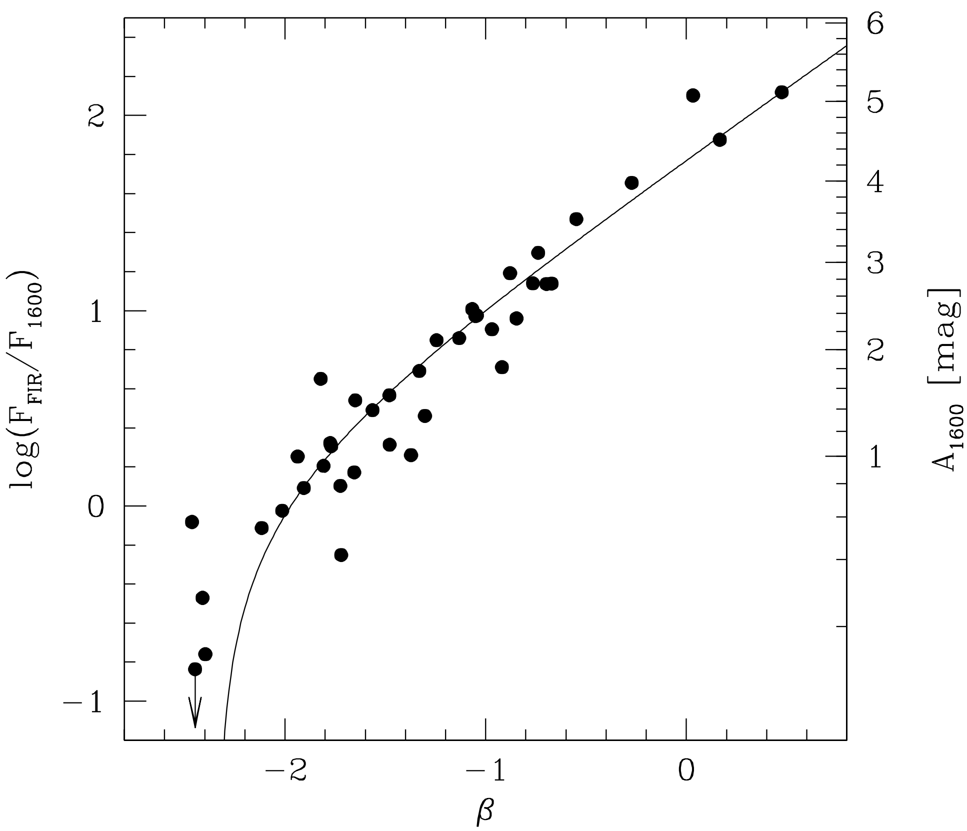

Figure 1. The IRX-β correlation (from MMC99). The UV spectral slope β is plotted on the abscissa. On the ordinate is plotted IRX, the ratio of fluxes in the FIR and and UV (at 1600Å). At right IRX is converted to the effective UV extinction A_{1600}. The data points represent the UV-bright starburst sample of MMC99, derived from the IUE atlas of star forming galaxy (Kinney et al. 1993). The curve is a simple linear fit of A_{1600} as a function of β.

properties, then the IRX-β relationship would over predict their contribution to the total SFRD at $z \sim 3$.

Fortunately, while LBGs in general are not individually visible at other dust-insensitive wavelengths, stacked measurements of fluxes in the radio and X-ray can be used to test whether LBGs have similar dust extinction properties as nearby UV-bright starbursts.

The radio result is given as a note in proof to MHC99 and repeated in Table 3. Radio fluxes of the the ten U-dropout galaxies in the Hubble Deep Field North (HDF-N) with the highest predicted 850μm SCUBA fluxes were computed by assuming that the galaxies obey the local FIR to radio correlation, have a radio spectral slope $\alpha = -0.7$ ($f_\nu \propto \nu^\alpha$) and that the FIR flux is the reprocessed UV flux. The stacked radio fluxes, kindly provided by E. Richards, agree remarkably well with the predictions for these ten sources. AS00 also do an analysis of the stacked LBG fluxes at 20cm using the Richards et al. radio map. Their total observed and predicted fluxes are $105 \pm 81\,\mu$Jy and $114 \pm 36\,\mu$Jy respectively, similar to what is reported in MHC99 but with larger errors. The difference is in part due to AS00 stacking *all* their 46 HDF LBGs for the analysis. This includes many with very little predicted flux which contribute the majority of the error budget. In addition, AS00 derive a higher error per beam by integrating over the beam, which overestimates the error per source. Hence the stacked radio flux estimate is probably more significant than implied by AS00.

Table 3. Sum of radio fluxes: HDF U-dropouts with the ten brightest predicted 850μm fluxes (MHC99).

Wavelength (cm)	Flux density (μ-Jy) predicted	observed
3.5	28	27 ± 5
20	100	105 ± 24

X-rays can also be used to probe high-z star formation. The Chandra soft X-ray band corresponds to 2-8 Kev at $z = 3$, "hard" enough to pass through the ISM of galaxies virtually unattenuated. Seibert, Heckman & Meurer (2002) compared the stacked soft X-ray flux of HDF-N AGN free U-dropouts given by Brandt et al. (2001) with predictions from dust reddening models. The results are consistent with a variety of plausible dust reddening laws including the IRX-β correlation from MHC99, the Calzetti et al. (2000) starburst "obscuration curve", and the homogeneous and clumpy foreground dust screen models from Witt & Gordon (2000). The results are not consistent with the rest-frame UV flux from LBGs being like that of ULIRGs which have IRX values on the order of 10^2 to $10^{3.5}$ (Goldader et al. 2002). In fact, if LBGs had similar values they would be easily observable individually in X-rays, the sub-mm, and radio (and they are not). Similarly the scenario that LBGs are not extincted at all under-predicts the stacked X-ray flux by a factor of six. Nandra et al. (2002) do an independent analysis of stacked X-ray results in the HDF-N from Chandra and reach similar conclusions.

The stacked radio and X-ray analyses are both consistent with the local starburst reddening relation applying to high-z LBGs. If so, then they would dominate total SFR density at $z \approx 3$ (AS00). However, there may be a fly in the ointment. As earlier mentioned, in the MHC99 and AS00 picture we would expect the LBGs to have 850μm fluxes up to $\sim$ 1 mJy. While such fluxes are at or below the confusion limit of blank field SCUBA observations it may be possible to detect such sources through gravitational lensing. Smail et al. (2002b) constrain the faint counts at 850 μm using SCUBA observations towards lensing clusters. A little over half of their sample are undetected in their HST I images, with the non-detections preferentially being at the (sub-mm) faint end. These faint end sources have magnification corrected 850μm micron fluxes like the predictions for LBGs. The implication is that the LBGs are not showing up in SCUBA observations presumably because the local IRX-β relationship overpredicts their 850μm flux as it does for MS1512+36-cB58. Instead the 850μm background is actually dominated by star forming galaxies like local ULIRGs (Goldader et al. 2002) - totally hidden by dust, as is also the case with the brightest SCUBA sources.

While this scenario may be correct, a careful examination of Smail et al. (2002b) suggests that it is built on a shaky foundation. Their claim to having resolved the 850μm background rests on four faint ($S/N = 3$ to 5) 850μm detections. These have only have lower limits to their magnifications (presumably because their positions are uncertain, since they have no optical, NIR, or radio counterparts). Their Monte-Carlo simulations indicate that at least one of these sources should have a source plane 850μm flux in the 0.5 to 1 Jy range, the only sources in their survey that could be that faint (or fainter). However, using the lower limit magnifications shows that none of the source plane fluxes need actually be fainter than 1.6 Jy, while the brightest predicted 850μm flux for the LBGs in the HDF-N is 1.8 mJy (MHC99). Smail et al. are not convincingly dipping deep into the expected realm of LBGs with their SCUBA observations. The lack of optical counterparts at the faint end also does not thoroughly rule out the presence of LBGs. They state a detection limit of $I \sim 26$ in their HST images which corresponds to a typical brightness seen in LBGs. However, this is the detection limit at $S/N = 2$ for a point source. To do this well the detection limit should be stated at a higher S/N (at least 3) and be calculated for typical LBG sizes (corrected for lensing in their case). I expect this would lower the limiting mag to $I \sim 25$ or brighter. Figure 15 of AS00 implies that the optical counterparts of the $\sim 1-2$ Jy sources have magnitudes over a wide range $I \sim 24$ to 27 ABmag in the source plane. Smail et al. have not convincingly ruled this out yet.

I conclude that the nature of the sources dominating the sub-mm background is not yet well determined. It is clear that the leading contenders are galaxies at $z \gtrsim 2$ whose bolometric output is dominated by dust, and that these galaxies dominate the star formation rate density at these redshifts. It is not yet settled whether these galaxies are detectable in the rest-frame UV. Additional observations of lensing clusters in the mm and sub-mm would improve the statistics on the 850μm counts at and below 2 mJy, while deeper optical observations of the faintest SCUBA sources (e.g. with ACS on HST) are needed to make a fair and convincing test of the LBG scenario.

4. What the future holds

High redshift observational cosmology is one of the most active fields of astronomical research, as can be seen by sifting through the daily offerings on astro-ph. Progress is rapid and happening on many fronts.

The installation of the Advanced Camera for Surveys on HST in 2002 allows routine optical imagining to Hubble Deep Field depths in fields with twice the area and angular resolution of WFPC2 (Ford et al. 2002). The first ACS results from the GOODS project (Giavalisco et al. 2003) are soon to come out in a special ApJ Letters volume. The results include reported color evolution in the LBG population, suggesting less dust is present in the $z \sim 4$ population compared to the $z \sim 3$ population (Idzi et al. 2003; Papovich et al. 2003).

The recent successful launches of the GALEX[1] and SIRTF[2] satellites will allow excellent survey capabilities in the vacuum UV ($0.13 - 0.3\,\mu$m) and infrared (3.5 – 160 μm) respectively. Together they will provide the definitive local calibration of the IRX-β relationship. GALEX will extend the redshift range for LBG selection to $z < 2$. The SIRTF observations of the GOODS project will directly detect normal galaxies and LBGs out to $z \sim 5$ LBGs at $3.5 - 8$ μm(rest frame NIR) which allows probing of their evolved stellar populations. At 24 μm they should also be detect rest frame ~ 7 μm reprocessed PAH emission from galaxies with $L_{\rm FIR} \gtrsim 10^{11}$ out to $z \sim 2$.

Recent progress in sub-mm galaxy research includes an improved efficiency in obtaining redshifts. Chapman et al. (2003b) present optical redshifts for 10 sub-mm sources also detected in the radio. Soon that group will publish an expanded sample of about 70 optical spectroscopic redshifts of sources detected at both radio and sub-mm wavelengths. They find that sub-mm galaxies mostly do indeed have the high redshift ($z \sim 2.5$) that was expected. This work provides the first accurate redshift distribution and space density measurements of the sub-mm population. While more progress could be made in identifying the faintest SCUBA sources (as outlined in § 3), what is really needed is more and reliable detections of the $\lesssim 1$ mJy population, i.e. somewhat *below* the confusion limit. It seems unlikely that there will be enough clusters not already looked at by the Smail, Blain, Ivison group and other SCUBA researchers to add substantial numbers of faint sources.

Unfortunately, at the longest wavelengths (160 μm), the SIRTF PSF has FWHM $= 38''$ and hence the detections will also be confusion limited at around 7 to 19 mJy (Xu et al., 2001), and thus SIRTF is not likely to settle the debate on the source composition of the sub-mm/FIR background. SOFIA will provide higher resolution imaging ($\sim 8''$ at 200μm) but due to the high sky background

[1]http://www.galex.caltech.edu/

[2]http://sirtf.caltech.edu/

will generally be limited to galaxies with $z < 1$[3]. Bolometer arrays larger than SCUBA, such as SCUBA-II[4] also will not address this issue since it is angular resolution, and hence telescope aperture that limits us from resolving the FIR - mm background. Existing or soon to be completed sub-mm to mm arrays such as the SMA[5] will help to pin down the position of the brightest SCUBA sources. However, to truly resolve the sub-mm to mm background we must await significant completion of ALMA – the Atacama Large Millimeter Array[6]. When completed in 2012 it will be able to reach flux densities of ~ 0.1 mJy (well into the expected fluxes of LBGs) in about half an hour at 850 μm. With a resolution of $0.1''$ or better (depending on array configuration) the observations should be well out of the confusion limit. Combining ALMA data with (then ancient archival) data from HST and hopefully new data from JWST (the James Webb Space Telescope) will allow a direct estimate of the bolometric output, and hence star formation rate, of all types of high-z galaxies. This will make the question of whether galaxies obey the IRX-β relationship somewhat moot.

5. Summary

The papers reviewed here have shown strong evidence that almost all types of high-z sources contain dust. The only case where the evidence is not yet convincing is the quasar absorption line systems, particularly at the column densities of the Lyman forest. In that case, it is not even clear that we are dealing with galaxies. All other cases involve galaxies with at least some inferred star formation. Hence at high redshift, as in the local universe, star formation and dust are correlated. The dominant location of high redshift star formation remains debatable. While it remains plausible that the majority of star formation at $z > 2$ remains completely invisible shortwards of the rest-frame FIR, there is a strong body of evidence that moderately dust obscured but rest-frame UV-bright galaxies should dominate the star formation in the early universe. It is likely that this issue will not be definitively settled until the sub-mm background is fully resolved.

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[3] http://sofia.arc.nasa.gov/Science/science/sci_opport_galaxies.html

[4] http://www.jach.hawaii.edu/JACpublic/JCMT/JCMT_developments/SCUBA2/scuba2.html

[5] http://sma-www.harvard.edu/

[6] http://www.alma.nrao.edu/

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