ICE EMISSION AND THE REDSHIFTS OF SUBMILLIMETER SOURCES

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ABSTRACT

Observations at submillimeter wavelengths have revealed a population of sources thought to be at relatively large redshifts. The position of the 850 μm passband on the Rayleigh-Jeans portion of the Planck function leads to a maximum redshift estimate of z ~ 4.5, since sources will not retain their redshift-independent brightness close to the peak of the Planck function and thus drop out of surveys. Here we review evidence that ice absorption is present in the spectra of local ultraluminous infrared galaxies, which are often taken as analogs for the 850 μm source population. We consider the implication of this absorption for ice-induced spectral structure at far-infrared wavelengths and present marginal astronomical evidence that amorphous ice may have a feature similar to crystalline ice near 150 μm. Recent corroborative laboratory evidence is supportive of this conclusion. It is argued that early metal enrichment by pair-instability supernovae may lead to a high ice content relative to refractory dust at high redshift, and a fairly robust detection of ice emission in a z = 6.42 quasar is presented. It is further shown that ice emission is needed to understand the 450 μm sources observed in the GOODS-N field. We are thus encouraged to apply far-infrared ice emission models to the available observations of HDF 850.1, the brightest submillimeter source in the Hubble Deep Field. We suggest that a redshift as large as 13 may need to be considered for this source, nearly a factor of 3 above the usual top estimate. Inclusion of the possibility of far-infrared ice emission in the spectral energy distributions of model sources generally broadens the range of redshifts to be considered for submillimeter sources compared to models without ice emission.

Subject headings: galaxies: formation — galaxies: high-redshift — galaxies: individual (HDF 850.1, IRAS 00188−0856, IRAS 14348−1447, QSO J1148+5251) — infrared: galaxies

1. INTRODUCTION

Sources discovered in surveys undertaken using the 450/850 μm SCUBA camera mounted on the James Clerk Maxwell Telescope have a high number density per unit solid angle (~10⁴ deg⁻²; S₅₅₀ > 1 mJy; Sanders 2000; Wang et al. 2004) and are thought to trace the dust emission from sources at a range of redshifts. Sources brighter than 1 mJy which have Arp 220–like far-infrared (FIR) spectral energy distributions (SEDs) are ultraluminous in the h₁₀₀ = 0.71, Ωₘ = 0.27, and Ωₐ = 0.73 cosmology consistent with cosmic microwave background (CMB) and Type 1a supernovae (SNe) observations (Spergel et al. 2003; Nolta et al. 2004; Riess et al. 2004) unless they are at redshifts <1 so that, thus far, submillimeter surveys do not detect “normal” galaxies at high redshift. This should be the case even for gravitational lens amplification up to a factor of 4 for 2 mJy limit surveys.

It is therefore a sensible approach to consider the properties of local ultraluminous infrared galaxies (ULIRGs; Sanders & Mirabel 1996) as a guide to understanding sources detected in submillimeter surveys with the proviso that the high-redshift universe may not conserve these properties. It has already been noted that the number density of ULIRGs increases with redshift at a rate much larger than can be explained using geometric considerations alone (Kim & Sanders 1998), and deep field observations using the Hubble Space Telescope have found quite obvious morphological evolution at higher redshifts compared to local conditions (e.g., Brinchmann et al. 1998). While these particular evidences of evolution as a function of redshift do not directly speak to ULIRG SED evolution, they do suggest that this proviso cannot be lightly discounted.

Ice is present in the dense interstellar medium (ISM) of the Galaxy. It is observed to occur above a threshold depth of Aᵥ ~ 3 within molecular clouds, but is absent on the cloud edges and in the diffuse (atomic/ionized) ISM (Whittet et al. 1988). Because ice is not exposed to starlight, FIR emission from ice is not expected from quiescent clouds. The FIR emission from these ice-bearing clouds arises from the first few ice-free Aᵥ. To observe ice emission in the Galaxy, centrally heated sources are needed. If mid-infrared (MIR) radiation can illuminate the ice-bearing grains so that they may be heated, then the FIR emission will be dominated by ice if the ice mantles provide a moderate fraction of the total grain volume. This FIR dominance is owing to greater FIR opacity of ice relative to silicate or carbonaceous grains. In the models presented by Aannestad (1975) a mantle-to-core volume ratio of 0.33 doubles the 60 μm opacity: a 10% increase in grain radius doubles the opacity!

Protostars in the Galaxy which are centrally heated turn out to be good sources for observing FIR ice emission (e.g., Dartois et al. 1998). And, there is mounting evidence that a significant fraction of local ULIRGs are also centrally heated (Dudley & Wynn-Williams 1997; Soifer et al. 2002; Imanishi & Dudley 2000;
Imanishi & Maloney 2003; Imanishi et al. 2006; Spoon et al. 2006), so that the FIR emission is a result of MIR heating. Thus, if ice is present in the FIR-emitting regions, its effects on the FIR opacity may be important. This situation differs from what occurs in lower luminosity starburst galaxies where the FIR emission arises from the surfaces of molecular clouds, which are heated by optical and far-UV rather than MIR light. The interiors of the clouds, where ice presumably exists, are not strongly heated by the mainl FIR emission arising from their surfaces.

If submillimeter galaxies are similar to ULIRGs in more than just their luminosity, then they may also sometimes have FIR emission that is powered by MIR light. For redshift estimation the question of the similarity between submillimeter galaxies and local ULIRGs is as important as the differences that distinguish ULIRGs from their lower luminosity starburst counterparts.

Attempts to estimate redshifts for the submillimeter sources based on their radio fluxes could be guided by local ULIRG samples. For the 13 ULIRGs brighter than 5.24 Jy at 60 μm (Soifer et al. 1987; Sanders et al. 1995) available to the Very Large Array, the mean logarithm of the ratio of FIR to 20 cm radio flux is 0.22 dex larger than $q = 2.43 \pm 0.19$ (Condon et al. 1991) for starburst galaxies when calculated using radio measurements reported by Condon et al. (1991) and Yun et al. (2001). While the mean differs at only the 1 σ level, the dispersion of $q$ is a factor of 1.6 (in dex) larger than for the lower luminosity star-forming galaxies. Using a different luminosity binning, Helou et al. (1985) report a similar trend in increased dispersion with increasing luminosity. The implication for redshift estimation is that the range of likely redshifts would increase when using ULIRG properties rather than starburst properties. And, a trend away from what is seen in local ULIRGs, say through more powerful starbursts at earlier times, could have complex implications for estimating redshifts of submillimeter galaxies using radio observations.

However, broad limits on the redshift distribution derive from submillimeter observations alone where the relative infrequency of detecting 450 μm emission leads to (weak) lower limits on the redshifts, while the detections themselves at 850 μm lead to upper limits since, barring extraordinary luminosities, the turnover from the Rayleigh-Jeans-like portion of the SED at high redshift leads to source fluxes dropping below survey detection limits.

Given the large potential effect of ice on the FIR opacity of submillimeter galaxies, we first review the evidence for the presence of ice in centrally heated ULIRGs and estimate an expected FIR SED for a case where FIR ice opacity can be expected to be dominant based on a rough abundance analysis. We then search for FIR ice spectral features in the available data on ULIRGs. We discuss why a high relative abundance of ice during the epoch of reionization might be expected and present somewhat firmer evidence for FIR ice emission in the $z = 6.42$ source QSO J1148+5251 than can yet be demonstrated for ULIRGs. We then take the submillimeter galaxy HDF 850.1 as an example to show how FIR ice emission allows a very large redshift estimate.

2. ICE IN ULIRGs
2.1 Absorption

Observations of strong absorption features from refractory dust in ULIRGs trace dust that is cooler than the temperature of a blackbody emitting at the wavelength of the feature: ~300 K for the 10 μm silicate feature and ~150 K for the 20 μm silicate feature, for example. Thus, 20 μm silicate features are weak in ULIRGs compared to 10 μm features owing to the dust radial temperature gradient. Ice absorption, on the other hand, should only occur in the cooler outer regions of the dust envelope and so may show the same relative feature strengths found in the laboratory, unless the absorbing covering factor is a strong function of the emitting source’s wavelength-dependent size [buried source radius $r \approx 0.8(L/10^{12} L_\odot)^{0.5}(λ/3 \ μm)^2$ pc, where $T$ has been eliminated between the Wein displacement and Stefan-Boltzmann laws, $L$ is the portion of IR luminosity corrected for extended star formation, $z$ runs from 2 μm to the lesser of either the wavelength where the source is no longer optically thick or the peak FIR wavelength, and scattering is neglected]. MIR ice absorption is therefore consistent with a portion of the FIR emission being powered by the MIR rather than the optical and UV portion of the electromagnetic spectrum. However, it is necessary to be certain that the reported absorption is indeed owing to ice. As an example, Spoon et al. (2004) claim ice absorption in 18 galaxies based on 6 μm absorption including IRAS 17208−0014, the third brightest ULIRG. However, OH bond bending need not occur in ice alone. The absence of 3 μm absorption in the spectra of the dust-continuum-dominated sources Mrk 231 and IRAS 05189−2524 presented by Spoon et al. (2004), where veiling by starlight is unimportant, suggests that an identification of water ice may be premature for these sources, and refractory materials such as those studied by Greenberg et al. (1995) may provide a more convincing model. An apparent 6 μm dip in the spectrum of Mrk 231 plotted by Weedman et al. (2005), similar in amplitude to the 6.2 μm hump for which they report a measurement, tends to confirm the Spoon et al. (2004) claim of 6 μm absorption in this source. The spectrum of Arp 220 may be consistent with a contribution of 12.5 μm libration mode absorption, supportive of the Spoon et al. (2004) identification of ice absorption in this source, but, until recently (Imanishi et al. 2006; Risaliti et al. 2006; Imanishi 2006), the only well-confirmed case of ice absorption among ULIRGs in their sample was that of IRAS 00188−0856, where ice absorption at 3 μm confirms the identification (Imanishi & Maloney 2003). See Imanishi et al. (2007) for further well-confirmed ice identifications.

To illustrate this we present Figure 1, which employs a slightly detailed model to explain the absorption features observed between 2.7 and 12.4 μm. The upper panel reproduces the 3 μm spectrum reported by Imanishi & Maloney (2003) together with an absorption model composed of amorphous ice and refractory carbonaceous absorption applied to a power-law continuum, and veiled by some starburst-like emission. The model is then applied in the lower panel, with some adjustment made for expected reduced refractory absorption at longer wavelengths owing to a presumed dust temperature gradient. It has not been possible to fit the entire 3 μm absorption without using ice. Thus, the absorption at 6 μm also is partly attributed to water ice. With these data, 12.5 μm water ice absorption, while included in the model, does not seem to be required, so that one may conclude that two features, and particularly the degeneracy-breaking short-wavelength edge of the 3 μm absorption, contribute to the fairly robust identification of ice in IRAS 00188−0856. We note that the need for strong silicate absorption in this source is confirmed by the clear presence of 18 μm silicate absorption (Imanishi et al. 2007).

Thus, ice absorption could play a significant role in ULIRGs, but the evidence is not yet as strong as that showing that the MIR emission is often absorbed by refractory dust. Evidence for or against FIR ice emission or absorption in ULIRGs is in worse shape still. This is primarily owing to a lack of observational data. In Figure 2 we present archival Infrared Space Observatory Long Wavelength Spectrometer (ISO LWS) spectra of Mrk 231 (diamonds) and IRAS 17208−0014 (circles), which show spectral structure in the shortest wavelength detector band SW1. This structure is compared to the spectrum of the icy source
invoked for this source on a smaller physical scale to explain its low X-ray flux (Maloney & Reynolds 2000). For IRAS 17208−0014, the present spectrum would tend to confirm the Spoon et al. (2004) identification of the 6 μm absorption as do 3 μm spectra (Risaliti et al. 2006; Imanishi 2006). For either source, the presence of crystalline ice implied by the possible 43 μm absorption would imply a low cosmic-ray abundance at least in the region where the absorption is produced, since ion bombardment erases crystalline structure in cold ices (Moore & Hudson 1992). The inset in Figure 2 shows the relationship between the wavelength of the 43 μm peak and ice temperature measured by Smith et al. (1994), which we have invoked to shift the ice spectrum derived from HD 161796, an evolved ice-forming star (Hoogzaad et al. 2002), beyond the corrections made for the source redshifts to better match the spectra. Inversion of these corrections would imply temperatures at which amorphous ice may exist and would be preferentially formed. Constraints on cosmic-ray abundance would need account for the rate at which crystalline ice is introduced into the absorbing region either through (substantial) changes in luminosity of the source which may allow the annealing of amorphous ice to crystalline ice, processing of ice by local heat sources in the region, or the migration of crystalline ice into the region. The discovery of substantial radial molecular gas motion in the ULIRG IRAS 08572+3915 (Geballe et al. 2006) suggests the third possibility needs close scrutiny. Since the SW1 detector of LWS is problematic, these sources must be independently reobserved and the potential features confirmed before fully accepting that ice is present in these sources.

2.2. Millimeter Morphology

We have examined the LWS SW1 spectra of two other ULIRGS, Arp 220 and Mrk 273, finding no feature consistent with crystalline ice absorption. In the case of Arp 220, the FIR spectrum appears to be optically thick (González-Alfonso et al. 2004). There is every reason to think ice should be present owing to the source temperature, the clear presence of water vapor, as well as supportive MIR observations already mentioned. Here, ice may help to resolve an issue raised by Soifer et al. (1999) with regard to FIR sources that are optically thick, showing any detectable emission in the MIR owing to overwhelmingly large implied MIR opacity. Since ice...
strongly FIR opacity compared to refractory dust, a given FIR optical depth can be achieved with less dust, up to a factor of 7 in the models computed by Aannestad (1975). This effect can make the issue raised by Soifer et al. (1999) less troubling, although other approaches such as examining the effects of the dust density distribution (e.g., Nenkova et al. 2002) may also need to be explored as well. Ice may also have the effect of making millimeter continuum size estimates smaller than what might be expected for refractory dust that is optically thick in the FIR, since the opacity of ice-mantled grains is lower than that of bare grains at millimeter wavelengths. This could yield a cuspy morphology in the millimeter where one would usually expect a relatively more flattened morphology owing to the cooler outer regions being relatively brighter in the millimeter under the assumption of higher refractory dust opacity.

2.3. FIR Ice Spectrum

The infrared laboratory spectrum of crystalline water ice has been well known for some time (Bertie et al. 1969), and differences between the spectrum of crystalline and amorphous ice have been exploited to aid understanding of astronomical sources (e.g., Dartois et al. 1998). However, owing to the low thermal conductivity of amorphous ice, preparation of laboratory samples, via vapor deposition, that are thick enough to conduct investigations at wavelengths longer than 100 μm has been too difficult until recently. In particular it has been unknown whether or not amorphous ice has a feature corresponding to the broad feature centered near 150 μm identified by Bertie et al. (1969) as a phonon mode in crystalline ice. Since nature provides sources rich in amorphous ice, it may be that such a comparison could be made through observations of these sources. The spectral coverage of the ISO LWS spectrometer extended to ~200 μm, too short to fully cover the broad 150 μm crystalline ice feature. Comparison between the ISO LWS data presented by Dartois et al. (1998) for RAFGL 7009S, a deeply embedded ultracompact H II region, and the submillimeter observations provided by McCutcheon et al. (1995) yield a modified optically thin blackbody parameter set of $T = 27$ K, $\beta = 2.1$ (where the dust emissivity is proportional to $\lambda^{-\beta}$) when attempting to match data near 190 μm. The large value of $\beta$ is suggestive of the presence of a feature similar to that of crystalline ice in this amorphous ice-dominated source. However, full spectroscopic confirmation is needed to decide if the long-wavelength departure of the data from the model of Dartois et al. (1998) indicates the existence of an amorphous ice feature analogous to the 150 μm crystalline ice feature.

Laboratory work by Curtis et al. (2005) has explored the optical properties of amorphous ice between 15 and 200 μm. There is little question that most of the ice in the thick films used by Curtis et al. (2005) deposited at $T \leq 126$ K differs from ice deposited above this temperature, since the wing of the libration band is clearly shifted, so it seems safe to conclude that amorphous ice, clearly present in the thinner samples, is also largely present in the thicker samples despite issues related to the low thermal conductivity of amorphous ice, which hampers the (rapid) growth of thick samples. Gerakines et al. (2005) have also had recent success in growing thick samples of amorphous ice using low deposition rates. Schober et al. (2000) take a different approach: annealing samples of high-density amorphous ice into the low-density amorphous ice found in space. As with the LWS spectroscopy, the new amorphous ice optical constants (Curtis et al. 2005) do not extend to the wavelength regime (300 μm) where crystalline ice shows absorption whose wavelength dependence is described by $\lambda^{-4}$ (Bertie et al. 1969). Unlike natural sources, however, where temperature and grain size effects make full spectral coverage of a broad feature nearly absolutely necessary to ascertain its reality, the controlled laboratory conditions allow a reasonable extrapolation to be considered reliable. The finding of Curtis et al. (2005) that the imaginary part of the refractive indices of amorphous and crystalline ice are very similar between 100 and 200 μm would appear to be consistent with the suggestion of Schober et al. (2000) that the order in amorphous ice indicated by sharp features in inelastic X-ray scattering data may be owing to a hydrogen network that is also present in crystalline ice. If this order is indeed present, then a shared spectral structure for the interaction of FIR photons with phonons between the two types would allow a first-order substitution of crystalline ice optical constants for the unknown values for amorphous ice beyond 200 μm.

2.4. FIR Ice Emission

Turning to photometry, and returning to ULIRGs, if we accept the Spoon et al. (2004) classification scheme, then the spectrum of IRAS 14348–1447 as reported by Genzel et al. (1998) or Charmandaris et al. (2002) must be considered class II, that is, 6 μm “ice” absorption is present and partially filled in by 6.2 μm polycyclic aromatic hydrocarbon emission. This source occupies an extreme position in the dust emissivity ($\beta$) versus 100 μm optical depth ($\tau_{100}$) diagram given by Klaas et al. (2001) with both high $\tau_{100}$ (5) and $\beta$ (2). Since the effects of optical depth and emissivity are intertwined, a lower optical depth can imply a larger value of $\beta$. For example, $\beta = 2.4$ and $\tau_{100} = 0.1$ does about as well as the Klaas et al. (2001) parameters for data longward of 100 μm. However, values of $\beta$ larger than 2 are not generally found except where ice is thought to be present (e.g., Lis et al. 1998) or dust temperatures are lower than found in ULIRGs (67 K for the Klaas et al. [2001] fit, or 26 K at the lower optical depth and larger $\beta$ tested here). In Figure 3 we compare the fit proposed for IRAS 14348–1447 by Klaas et al. (2001) with an alternative model. The model shown by the dashed line is that of Klaas et al. (2001), while that shown by the thick solid line is a core-mantle grain model taken from Aannestad (1975) but modified to have amorphous ice features in the following way: First,
opacity data from Smith et al. (1994) for crystalline ice cooled to 70 K were matched to the Aannestad (1975) curve for \( V_m/V_c = 0.95 \) by inducing a \( \nu^{-1} \) dependence to approximate the Mie calculation results along with the addition of an underlying continuum opacity. Second, amorphous ice opacity data (Smith et al. 1994; deposited at 10 K and warmed to 70 K) were substituted to calculate a model with 16 and 71 K components. If we take temperature and optical depth as free parameters for the Klaas et al. (2001) fit (two parameters; normalization fixed by IRAS) and two temperatures, two optical depths, and the relative contribution at 90 \( \mu \)m of these two components as five free parameters for the present model, then we may estimate how well the two models represent the data if we know something about the errors in the data. The statistical errors for the data are thought to be small, but if we know something about the errors in the present model, then we may estimate how well the two models represent the data if we know something about the errors in the data.

We have thus assumed 13% errors for the ISOPHOT data to give a filter-to-filter accuracy of 20% (Klaas et al. 2000). The fit of Klaas et al. (2001) for data longward of 20 \( \mu \)m is unacceptable \( [P(\chi^2 , \nu) = 0.02] \) under our assumption about the errors. A marginally acceptable fit \( [P(\chi^2 , \nu) = 0.4] \) is found for the amorphous ice model. Detailed inspection of the ice fit suggests that the 150 \( \mu \)m ice feature is not accounting for all of structure in the data. The thin solid line (\( V_m/V_c = 0.33, T = 28.8 \) K; \( \tau_0 = 0.2 \) and \( V_m/V_c = 0.95, T = 85.0 \) K, \( \tau_0 = 0.08 \) crystalline ice; onion-skin model with warm, \( T = 180 \) K, refractory dust in the interior) shows that this might be possible. However, our method of substituting amorphous for crystalline ice is unlikely to work well for the thin mantle used here. Given the assumption regarding the data errors made here, it is not possible to make a clear claim that ice emission is detected in this source. Assuming larger errors could make both low free-parameter models acceptable while reducing the errors could make the simpler ice model unacceptable, while the more complex model cannot be evaluated via reduced \( \chi^2 \). Clearly, Multiband Imaging Photometer for Spitzer (MIPS) SED mode observations could be definitive, since the strong 70 \( \mu \)m curvature in the ice models cannot be produced with standard refractory dust.

Thus, both astronomical and laboratory FIR data leave questions about ice unanswered. Crystalline ice has a feature near 150 \( \mu \)m which has yet to be completely compared with amorphous ice. Comparison between crystalline and amorphous ice has been made near 40 and 60 \( \mu \)m, and they are quite distinct, whereas they are similar between 100 and 200 \( \mu \)m. Beyond 200 \( \mu \)m questions remain which are presently answered by extrapolation of the laboratory data and hints from the astronomical data. Substituting crystalline ice for more common (in space) amorphous ice to consider wavelengths longer than 100 \( \mu \)m could add to (systematic) uncertainties in photometric redshift estimation that cannot be well addressed without further observations or measurements. Regardless of the remaining issues concerning the 150 \( \mu \)m feature, for the main purpose of this work it is prudent to consider the most extreme consequences of crystalline ice emission on redshift estimation, which are examined after the next section.

3. ICE AT HIGH REDSHIFT

3.1. Pair-Instability SNe Enrichment

Just as interplanetary grains may preserve a record of the sources of ISM enrichment occurring at what is presently observed to be \( z = 0.43 \), the solid phase of the ISM at high redshift may also record the conditions of the earliest enrichment. Particularly for sources that contribute to the reionization of the universe \( (7 < z < 14; \text{Spergel et al. 2007}) \), scenarios which attribute substantial enrichment to pair-instability SNe early on may leave a mark on the solid phase of the ISM which could linger through some subsequent processing. A chief attribute of pair-instability SN enrichment is an early high abundance of oxygen relative to other metals that usually deplete to the solid phase of the ISM.

For example, a 186 \( M_\odot \) progenitor yields number abundance ratios of \( O:Si:C:S:K:56 Ni = 126:29:15:10:8:1 \) (Heger & Woosley 2002) which, after formation of CO (29 O removed), olivine (16 O and 4 Si removed), silica (50 O removed), and SO2 (20 O removed), leaves 9% of the oxygen available to form OH and H2O. For a 100 \( M_\odot \) progenitor, \( O:Si:C:52 Mg = 48:9:1 \) with little Si, S, or 56Ni, leaving 80% of the oxygen available to combine with hydrogen assuming the refractory solid state is MgO. In the absence of 56Ni, the formation of solids should be enhanced, since it may commence at a higher density in the supernova remnant (SNR). These estimates for the available oxygen are essentially lower limits; more complete treatments which consider the possibility that the ejecta are unmixed (Nozawa et al. 2003; Schneider et al. 2004; allowing the formation of graphite, for example) would leave an even larger fraction of oxygen available. Thus, we might expect grains with large mantle-to-core volume ratios to result from a period of pair-instability SN enrichment. The continued presence of these ice grains would depend on the rate of reprocessing of this initial solid phase in the ISM.

3.2. Ice Emission in a High-Redshift Quasar

The Gunn-Peterson trough in QSO J1148+5251 \( (z = 6.42; \text{Bertoldi et al. 2003a}) \) suggests that this source may be participating in the last phases of reionization (Fan et al. 2003). That the quasar exists indicates that the source has been contributing to reionization for some time, and we may take the beginning of reionization as an estimate of its age (~500 Myr), which gives a high average accretion rate for a black hole mass of \( 3 \times 10^9 M_\odot \) (Willott et al. 2003). Thus, it seems plausible that pair-instability SN-enriched material with a high ice content is being supplied toward the center of this activity as the black hole and presumably its stellar system grow in mass. On the other hand, ice also forms in the more evolved ISM of the Galaxy, so an indication of the presence of ice need not be fully attributed to ice-rich regions that might be formed by pair-instability SNe.

Figure 4 shows an indication that the rest-frame FIR emission from QSO J1148+5251 is better explained by ice than refractory dust emission. Three models are compared to photometric observations: (1) a refractory model (dashed line, \( T = 55 \) K; \( \tau_0 = 0.3; \beta = 2 \)) is similar to that given by Beelen et al. (2006), (2) a simple ice model (dot-dashed line, \( T = 43 \) K; \( \tau_0 = 0.4, V_m/V_c = 5.6 \) amorphous), and (3) a more complex ice model described below (solid line).

In Figure 4 it is not possible to formally assess the goodness of fit through a reduced \( \chi^2 \) calculation even for the refractory dust model (dashed line), since the number of free parameters (normalization, temperature, optical depth, and opacity index) is the same as the number of points to be fit. If one were to assume \( \beta = 2 \) owing to insufficient time since the first enrichment to produce large grains, then \( \chi^2 = 10.7 \), which strongly rules out \( [P(\chi^2 , \nu) = 0.001] \) this model. That the fit is done by eye probably does not affect this assessment, but a failure to account for systematic errors could, since different groups give 850 \( \mu \)m photometric estimates using the same data that vary by as much as the refractory dust model differs from the present data. By selecting a particular mantle-to-core volume ratio (5.6) we may comparatively
provide a single degree of freedom and obtain $\chi^2 = 3.9$ (dot-dashed line), which would indicate that the model is not fully ruled out by the data [$P(\chi, \nu) = 0.05$] and is an improvement on the refractory dust model, again with the proviso that we have only considered statistical errors. More elaborate (multitemperature) refractory dust or ice-mantled grain models can fit the detections essentially perfectly and are useful to calculate, as they can indicate what further observations would be decisive. The solid line in Figure 4 is such a model where $T = 71 \, \text{K}$; $\tau_{60} = 0.4$ is ice-mantled dust is obscured by $T = 24 \, \text{K}$; $\tau_{60} = 0.4$ is ice-mantled dust. A similar model using $\beta = 2$ refractory dust (not plotted; $T = 300 \, \text{K}$; $\tau_{60} = 0.1$) is obscured by $T = 18 \, \text{K}$; $\tau_{60} = 1$ dust) exceeds the plotted 400 $\mu$m upper limit (arrow in Fig. 4; 0.39 mJy $3 \sigma$; Bertoldi et al. 2003b) by a factor of 1.9 and is unphysical in a number of ways, including that the cool component is cooler than the CMB at $z = 6.42$. The ice models distinguish themselves from the plotted refractory dust model by being fainter by at least a factor of 4 at rest wavelength 400 $\mu$m (3 mm observed frame). The present upper limit does not distinguish these cases. Such a measurement should be possible using the Combined Array for Research in Millimeter-Wave Astronomy (CARMA). Determining the composition of the emitting material can also affect estimates of the dust mass and thus estimates of the amount of past enrichment (and star formation) in the QSO J1148+5251 system. For the present ice model, 7 times as much refractory dust would be needed to produce the same FIR opacity so that a lower level of total enrichment might be accommodated.

Finally, at high redshift, where theory suggests that we might most anticipate it owing to expectations about early ISM enrichment, we find evidence for FIR ice emission which, while still debatable, seems moderately persuasive and which can be relatively easily checked with further observations using existing telescopes. Now we may turn to our main theme. We have employed amorphous ice to consider IRAS 14348−1447 and QSO J1148+5251, but now we consider crystalline ice both because its effect on redshift estimation is the most dramatic and because ice may form at fairly warm temperatures in the SNRs associated with pair-instability SNe.

### 3.3. Ice Emission in 450 $\mu$m Submillimeter Sources

A set of sources that could be at high redshift and that demonstrate the effects of ice are reported by Pope et al. (2005). They are detected at 450 $\mu$m but not at 850 $\mu$m. We consider the seven sources tabulated by Pope et al. (2005) and two sources from the original list of Borys et al. (2003), which were recovered above 3.5 $\sigma$ by Pope et al. (2005). These have drawn our attention because the reported 850 $\mu$m upper limits indicate large values of $\beta$ (Borys et al. 2004; based on original list). Large values of $\beta$ can indicate the presence of ice emission. If we generate 3 $\sigma$ lower limits to the 450 to 850 $\mu$m flux density ratios using the 450 $\mu$m measurements less $3 \sqrt{2} \sigma_{450}$ together with $3 \sqrt{2} \sigma_{850}$ $850 \mu$m upper limits, then the lowest lower limit is 8.7 and is only one of two that can be consistent with $\beta < 2$ dust. This method of calculating limits can be more conservative than calculating the ratio of the 450 measurement to the 850 $\mu$m 3 $\sigma$ upper limit (giving 13.4 in this case), but its extension to 2 $\sigma$ should be viewed with caution, since detections at the 2.9 $\sigma$ level are customarily reported as 3 $\sigma$ limits. In such situations, when data with comparable signal-to-noise ratios become available, the “2 $\sigma$ extension” may be violated much more frequently than the name implies if many of these near misses lurk in the original data. However, Pope et al. (2005) report no detection from applying the method of Caillault & Helfand (1985) (stacking) to the 850 $\mu$m data at the positions of the 450 $\mu$m sources they detect above 3.5 $\sigma$. In five cases where upper limits are calculated below we substitute the ratio of the 450 $\mu$m 3 $\sigma$ upper limit to the 850 $\mu$m measurement when it gives a more conservative value.

In Figure 5 we plot, as a function of redshift, the 450 to 850 $\mu$m flux density ratio calculated for a series of SEDs. The dashed line is for a model with $T = 60 \, \text{K}$, $\beta = 2$, and $\tau_{60} = 2$. On this line are plotted at $z = 0.9$ and $z = 0.5$ the 3 $\sigma$ lower limits (filled circle and diamond) for SMM J123603+620942 and J123631+620657. The arrows in the figure extend to the 2 $\sigma$ lower limits. In these cases the argument given by Borys et al. (2003) for $z < 1$ may be applied directly, although tenuously, at the 3 $\sigma$ level with no assumptions about ice, but this is not the case for the remaining lower limits. There may be some difficulty, however, accommodating these two sources at these low redshifts unless sources with 0.2−2 Jy level flux densities are present at 70 $\mu$m, while Frayer et al. (2006) find about four −30 mJy sources at 70 $\mu$m in this region, and we are unaware of any IRAS sources in this field. At these low redshifts, it is a losing proposition to attempt to increase the dust temperature to increase the redshift to avoid the
70 μm constraint in an effort to avoid requiring ice emission. When ice is invoked, then these and the remaining lower limits may all be accommodated, but the range of consistent redshifts expands. The remaining curves in Figure 5 correspond to increasing ice temperature. The dot-dashed curve uses a SED similar to that shown in Figure 1 (T = 30 K), the triple-dot–dashed curve has T = 50 K as in Figure 7, and the solid curve has T = 150 K; \( \tau_{24} = 0.04 \) and \( V_a/V_c = 5.6 \) for all ice models. For the solid curve, ambiguity between amorphous and crystalline ice is physically resolved in favor of crystalline ice. The SMM J123603+620942 and J123631+620657 limits are replotted on the solid curve, giving a redshift limit \( z < 10.2 \). This limit is little changed if the maximum possible ice temperature (170 K) is used. All the 3 σ limits can be accommodated at \( z = 9.5 \), but only SMM J123603+620942 and J123631+620657 can also be accommodated there at the 2 σ level. SMM J123657+620333 (filled square) shows this clearly where it is plotted at \( z = 9.6 \). The 2 σ level for SMM J133747+621600 (cloverleaf) also constrains the ice temperature to be \( T \geq 40 \) K. It is plotted on the \( T = 30 \) K curve at \( z = 1.9 \). The remaining sources other than SMM J123727+621042 are plotted with redshift upper limits well within the epoch of reionization. However, as with sources plotted on the \( T = 30 \) K curve, the 2 σ limits cannot be accommodated for \( z \geq 2.5 \). That seven of nine of the 450 μm sources in the Great Observatories Origins Deep Survey–North (GOODS-N) field require ice to explain the 850 μm nondetections without recourse to any other constraint suggests strongly that the possible effects of ice emission must be considered when interpreting submillimeter observations. Ice dramatically changes redshift limits: by a factor of 20 for SMM J123631+620657.

From the other direction, for the sources with 850 μm detections and 450 μm upper limits that also have estimated redshifts (Borys et al. 2004) we may also begin to constrain the presence of ice. Fourteen upper limits are plotted in Figure 5 as open circles for sources where a redshift estimate is given. The open diamonds are also upper limits plotted (but without arrows to avoid crowding) at the lower limits to their redshift given by Borys et al. (2004). For redshift estimates with \( z < 3 \) the upper limits are constraining on the likelihood that optically thin ice contributes to the FIR opacity: at the 2 σ level (arrowheads) little \( T > 30 \) K optically thin ice seems to be needed. At the 3 σ level, 4 of 11 sources could be consistent with a contribution of optically thin ice emission to the source SEDs. One source with a redshift lower limit (\( z > 2.7 \); SMM J123652+621225) needs to be optically thick and cool (\( T \sim 40 \) K) or at a higher redshift, as already noted by Borys et al. (2004). The remaining sources with redshift estimates above 3 or redshift lower limits are not constraining on the presence of ice. The present considerations suggest that the 450 and (\( z < 3 \)) 850 μm–detected sources differ physically in that the former have optically thin ice emission that dominates their FIR opacity, while the latter may be optically thick at 850(\( 1 + z \)) μm, or that refractory dust dominates their FIR opacity, or both. The average 450 to 850 μm ratio for the 850 μm source calculated from the stacked 450 μm and the average of the 850 μm flux densities reported by Pope et al. (2005) is 0.5, which we have plotted as a small open square at \( z = 4.25 \). The plotted redshift would be consistent with \( T = 30 \) optically thick material or \( T = 20 \) optically thin ice or \( \beta = 2 \) dust. If it is true that 850 μm sources are on average fainter at 450 μm than at 850 μm, then it seems as though many of the 850 μm sources must lie at \( z > 4 \) and ice may be needed to make them detectable at 850 μm with ULIRG luminosities (see end of \( \S \) 4.2). We do worry, however, that the stacked 450 μm flux is underestimated owing to the smaller 450 μm beam or that the data were normalized prior to stacking, making the reported units ambiguous. QSO J1148+5251 is also plotted (small filled circle). As discussed above, it seems to require ice emission. Just as detected 850 μm sources must be at least ultra-luminous, so also must the detected 450 μm sources be hyper-luminous (\( L > 10^{13} L_\odot \)). In Figure 6 we plot the models shown in Figure 5, giving their 450 μm brightness as a function of redshift under the following assumptions about luminosity: the models for refractory dust, and ice at \( T = 30 \) and 50 K are 10 times more luminous than ULIRG IRAS 00188–0856 (Fig. 1), the model for \( T = 150 \) K ice is 10 times more luminous still, and we have also plotted the complex amorphous ice model for QSO J1148+5251 at its observed luminosity (short-dashed line and circle; \( \sim 10^{13} L_\odot \); Beelen et al. 2006). The brightnesses of the 450 μm sources given by Pope et al. (2005) lie in the range 77–291 mJy, so that the plotted models would need to be scaled up by a factor of a few to cover this range fully unless the sources are at \( z < 0.2 \). For example, one of the brighter sources (SMJ J123631+620657; 263 mJy) would have a luminosity of 6 × 10^{14} L_\odot for the \( T = 150 \) K ice model if located at \( z = 9.5 \), a factor of 3 higher than the most luminous hyperluminous source listed by Verma et al. (2002). Its luminosity would be 10 times lower for the \( T = 30 \) K ice model located at \( z = 2 \), near the middle of the distribution of luminosities in their list. From Figure 5 we estimate that the 450 μm sources would populate the redshift ranges 1–3 and 5–10, with the latter range having a larger comoving volume by a factor of 1.7. If ice is only important close to reionization so that the sources were all at \( 9.2 < z < 10.2 \) (see solid line in Fig. 6), then the luminosities require about a tenth of the stellar mass of M87 per source to be involved in star formation. The space density would be 2.5 × 10^{-5} Mpc^{-3}, comparable to the local density of clusters of galaxies (Bahcall et al. 2003), and the luminosity density would be \( \sim 5 \times 10^{9} L_\odot \) Mpc^{-3} (comoving), about a factor of 100 higher than the local FIR value (Saunders et al. 1990). This would then imply a minimum of 10^3 recombinations per proton if the 450 μm luminosity traces a factor of 10 smaller ionizing luminosity: about 10^2 more
recombinations than for the lifetime of a typical H II region, which seems too high for reionization unless dust competes efficiently for reionizing photons.

On the other hand, there are six 850 μm sources with flux densities above 20 mJy listed by Pope et al. (2005) which could be close to hyperluminous (see Fig. 7), so that we need only postulate a similar population which is (thus far) invisible at 850 μm owing to the effects of ice, and thus expect to find these sources at a range of redshifts.

There is very clear evidence of ice rather than dust providing the FIR opacity in seven of the nine 450 μm sources considered here. But, the redshifts may or may not be high, and additional photometry is needed to constrain the redshifts.

4. HDF 850.1 AND ICE

4.1. z = 5

The search for counterparts at other wavelengths to the brightest 850 μm source in the Hubble Deep Field has been arduous, but Dunlop et al. (2004) make a convincing case for detections in the radio and near-infrared (NIR) and summarize submillimeter observations. Modeling (Aretxaga et al. 2003) of these observations leads them to conclude that the redshift of HDF 850.1 lies in the range 4.1 ± 0.5. Since the SED of a high-q ULIRG (IRAS 08572+3915) is included in the 20 templates in the model input, the effects of the change in the radio-FIR relation for ULIRGs compared to lower luminosity galaxies noted in § 1 should be partly represented in their estimate. Similarly, the suggestion of ice emission in the SED of IRAS 14348−1447 (Fig. 3) could also influence the estimate if the photometric data were used directly rather than fitted with a modified blackbody. In general, reliance on modified blackbodies will give lower estimated redshifts for cooler sources when more than one point on the Rayleigh-Jeans curve is available, as is the case for HDF 850.1, but the addition of an ice emission feature can increase the estimated redshift even for a cool source.

As one example, the bow tie shown in Figure 1 on the FIR continuum corresponds to the range of redshift one would calculate for HDF 850.1 based on two estimates of its 850 μm flux density (Dunlop et al. 2004; Wang et al. 2004) and the 1.3 mm flux density reported by Downes et al. (1999). That is, 5.4 < z < 5.6. It should be noted, even before describing the model on which this is based, that a detailed comparison between the SED shown in Figure 1 and the optical and NIR limits and detections for HDF 850.1 is not possible, owing to insufficient wavelength coverage for IRAS 00188−0856. See Dunlop et al. (2004; their Fig. 6) for a comparison with data from two ULIRGs and a luminous infrared galaxy calculated for a range of redshifts. However, the effects of FIR ice emission can be demonstrated with this example. The model, the short-dashed line in the lower panel of Figure 1, is based on curves given by Aannestad (1975), which are the results of calculations of the optical properties of ice-mantled crystalline silicate grains. And, it is crystalline water ice in the mantles. We chose the mantle-to-core volume ratio = 5.6 curve to most closely match the ratio of 3 μm ice to silicate optical depth used in the model shown by the solid lines in Figure 1. For a number of reasons this choice is probably not fully constrained by this ratio: the optical depth to which the silicate absorption is sensitive may be larger than for ice; an odd shift in the wavelength of the silicate feature may indicate a pyroxene composition with a different feature-to-continuum optical depth ratio than usual; the crystalline silicate in the Aannestad (1975) calculation is somewhat dissimilar to astrophysical silicate models. However, the first two effects may be compensating so that as a rough abundance analysis, the expectation that ice would dominate the FIR opacity in this source seems well founded. This condition, and the need for the ice emission to be moderately optically thin, are really the only two requirements for ice to strongly affect redshift estimation. The optical depth of the model of FIR emission shown in the lower panel of Figure 1 is set to correspond to the 3 μm ice optical depth used in models shown by the solid line in the upper panel (where ice and refractory material contribute equally to the absorption optical depth at 3.1 μm). The temperature of the FIR emission model is set to roughly reproduce the IRAS 60 and 100 μm measurements. This temperature also accentuates the effects of the broad 150 μm feature over which the HDF 850.1 data are displayed. The range of redshifts needed to place HDF 850.1 on this model falls outside of the range estimated by Dunlop et al. (2004) and gives a first indication that the effects of ice on photometric redshift estimation (as opposed to just limits) can be significant.

4.2. z = 13

As noted in § 1, using local ULIRGs to understand submillimeter sources is a sensible approach if their properties are not strongly affected by cosmic evolution. However, at higher redshift, this proviso seems fairly likely to break down. Many local ULIRGs appear to be produced in the mergers of gas-rich spiral galaxies, and it has been argued (Mihos & Hernquist 1996) that the dynamical stability provided by bulges may preserve gas reservoirs for the final merger stages associated with some ULIRGs. Owing to the finite lifetime of the universe, there are earlier
periods when the precursor systems may not resemble present-
day precursors in their dynamical state or star-to-gas mass ratio.
It is not at all clear that seed supermassive black holes (Osterbrock
1993) would be present at sufficient mass to allow accretion to be
an energetically important or dominant power source as suspected
for local ULIRGs (e.g., Imanishi et al. 2006). Thus, in what fol-
low we assume star formation as the main power source at
higher redshift. A sketch of how crystalline ice might exist in a
primordial galaxy environment is also given to explore the plau-
sibility of a very large effect of ice on redshift estimation. It is to
be noted that giving up a central power source such as would be
provided by an active galactic nucleus would usually mean that
ice-mantled grains would contribute little to the FIR emission,
since most of the energy that powers FIR emission would be ab-
sorbed in reactive photodissociation regions (PDRs) rather than
in molecular clouds where ice is thought to exist, unless an im-
probable scenario involving an overabundance of protostars
such as that proposed by Roussel et al. (2003) but previously
discounted by Dudley & Wynn-Williams (1997) is invoked. Below
we argue for such an overabundance.

In Figure 7 we show the observations of HDF 850.1 at \( z = 12.6 \) This is 18 confidence intervals beyond the Dunlop et al. (2004) estimate. So far as we can tell, neither the new Z-band
upper limit reported here, nor the released Spitzer Infrared Array
Camera (IRAC) and MIPS GOODS images (E. Dickinson et al.
2008, in preparation) rule out either the model shown in Figure 7
or the analysis of Dunlop et al. (2004), so long as a reddish
ULIRG (see Dudley [1999] for a discussion of 12 to 60 \( \mu m \) flux density ratios in ULIRGs) is used as a basis for the Dunlop et al. (2004) analysis. Dunlop et al. (2004) argue that the lensing source
(diamonds in Fig. 7) is evolved, in which case much of the ten-
sative observed frame 24 \( \mu m \) flux density could be owing to HDF
850.1, but little of the 8 \( \mu m \) flux density. At \( z = 4.1 \), Mrk 231
and 273 could be too blue to account for this level of emission,
whereas Arp 220 or IRAS 17208–0014 would not violate this
datum if treated as an upper limit. On the other hand, at \( z = 1.1 \)
the chances of finding a younger elliptical galaxy to act as a lens
are increased, so that some or all of the observed 24 \( \mu m \) flux den-
sity could be owing to the lensing galaxy. This would still not
rule out the Dunlop et al. (2004) redshift estimate for HDF 850.1,
but would accommodate the present estimate under the assump-
tion of the plotted starburst model. The shaded region in Figure 7
shows a possible range for the spectral shape of the lens source
emission. The source labeled 1b in Figure 8 of Wang et al. (2004)
may also contribute to the 24 \( \mu m \) emission, although only slightly
slightly to the IRAC data. If it is similar to NGC 253, and at a redshift
of \( z_{\text{ph}} = 1.76 \) (Fernández-Soto et al. 1999), then up to \( \sim 30\% \)
of the 24 \( \mu m \) flux density might be attributed to this source, but again
negligibly at 850 \( \mu m \).

The model for HDF 850.1 shown in Figure 7 (thick gray line)
is similar to that shown in Figure 1 in that it has the same mantle-
to-core volume ratio and optical depth; however, the temperature
is higher, as it must be owing to the higher CMB temperature at
\( z = 12.6 \). Whereas in Figure 1, the 150 \( \mu m \) ice feature spectral
structure influences the redshift placement of the HDF 850.1
data, in Figure 7, shorter wavelength spectral structure also
owing to ice is influential. Interestingly, assuming that there is a
foreground neutral intergalactic medium as a result of incom-
plete reionization (Spergel et al. 2007), one would expect Gunn-
Peterson saturation or a Ly\( \alpha \) blackout to occur in the \( H \) band
for \( z = 12.6 \), the shortest wavelength band for which HDF 850.1 is
detected. This is represented by the change from black to gray in
the thin line using a Heaviside function as multiplier. Here the thin

![Figure 8](image-url)
4.3. Why Star Formation?

Our choice of presenting a model that uses star formation as a power source may seem strange given that PDRs would be inefficient at producing ice emission, which we require to allow, for example, HDF 850.1 to be detected at \( z = 13 \). One phase of star formation that does allow MIR radiation to heat ice is the protostar phase. This phase is brief compared to O star lifetimes, and thus would not typically be expected to provide the dominant source of FIR radiation in a galaxy. Protogalaxies, however, are by definition required to be young, so that while the argument concerning the relative brevity of the protostar phase cannot be ignored, it may be overcome if the star formation rate is increasing rapidly with time. And, it is just such sources that one might expect to be observed as they populate the top of the infrared luminosity function, since they would be the most efficient at converting radiation to FIR wavelengths.

A rapidly increasing star formation rate might be expected in a situation where the gas cooling efficiency is increasing owing to ongoing initial enrichment. A positive feedback can lead to an exponentially increasing system response. The number at the right hand of Figure 8 shows the 850 brightness (in millijansky) of the three SED shapes considered here if we adopt the lensing amplification proposed by Dunlop et al. (2004) for HDF 850.1 for a source with the FIR luminosity of IRAS 00188 \( \pm 056 \). The increase in luminosity required to match the Hughes et al. (1998) estimate for HDF 850.1 would be a factor of 2.3 for the dashed curve taken at a redshift of 13. This would then correspond to \( \sim 4 \times 10^{12} L_\odot \) (e.g., Fig. 7) or \( 10^7 \) O stars and \( 1.5 \times 10^{11} \) G0 stars for a Salpeter initial mass function \( (m^{-2.35}) \), or roughly a galaxy’s worth of star formation. This then would be the limit for the continued exponential increase in the star formation rate: the amount of available enrichable gas. Night et al. (2006) find four objects with \( 10^{11} M_\odot \) in stars at \( z = 6 \) in their largest cosmological simulation (142 Mpc large enough to contain \( \sim 1 \) ULIRG at \( z = 0 \)). Thus, there is some suggestion that relatively massive objects (or perhaps regions that will become objects) are forming their stars a few dynamical timescales earlier than this. Notwithstanding the existence of QSO J1148+5251 and other high-redshift quasars, it seems to us that there is a need to account for massive sources at intermediate redshift which last formed stars near \( z = 13 \) (Stockton et al. 2004; Jimenez 2000), as well as the apparent monotonic increase in the comoving rate of gamma-ray bursts out to \( z = 7 \) (Le & Dermer 2007).

However, in the low-to-moderate redshift universe, we would usually take ice emission as an indication of a buried compact power source at least at ULIRG luminosities, and, should black hole growth commonly reach \( \sim 10^7 M_\odot \) by \( z = 13 \), as must happen at least occasionally given the existence of QSO J1148+5251, then our low-to-moderate redshift explanation could also apply during reionization.

5. SUMMARY AND PROSPECTS

Far-infrared (FIR) ice emission may be crucially important to understanding the FIR emission of sources at high redshift and may strongly affect the range of redshifts estimated for submillimeter sources, even placing them at reionization redshifts. Observations of infrared ice emission are definitive in Galactic protostars and the winds of evolved stars, but are scant and not fully persuasive for the local analogs of the submillimeter sources, the ULIRGs. This, despite mounting evidence that ice is involved in absorbing much of the energy that is finally emitted in the FIR in a substantial fraction of ULIRGs.

We find stronger indications that ice emission is important at high redshift. The data for QSO J1148+5251 as well as the 450 \( \mu m \) sources cataloged by Pope et al. (2005) are both strongly suggestive. We feel that further investigation along these lines could be quite fruitful.

We have considered two models where the presence of FIR emission features owing to ice in the SED of HDF 850.1 would place it at redshifts larger than the range estimated without ice by Dunlop et al. (2004). In the first, the use of crystalline ice at 150 \( \mu m \) as a substitute for amorphous ice is probably justified, subject to further laboratory investigations of amorphous ice. In the second, consideration of a first chemical enrichment mechanism suggests that crystalline ice could be present at early times, while energetic and timescale considerations may be compatible with protostars in protogalaxies producing the sort of features we consider here. In the second model, a \( \text{Ly}_\alpha \) blackout would be consistent with the NIR photometry for HDF 850.1. However, we do not prefer this model and its higher redshift over the redshift range estimated by Dunlop et al. (2004) or \( z \sim 5.5 \) from our first model. What we find to be important is that FIR ice emission could have such a dramatic effect on the estimated redshift. It should be noted that redshifts estimated from the radio-FIR relation could also turn out to be lower when ice emission is invoked, since a large submillimeter-to-radio flux density ratio is easier to produce with high-\( \beta \) at some redshifts. So, the main conclusion of this work is that ice broadens the range of redshifts to be considered for a given submillimeter source, and that ice is quite likely to be important at high redshift.

Some astronomical observations which could aid progress on open issues are as follows:

1. Continuum observations at 3 mm of QSO J1148+5251 may confirm ice emission in this source.
2. The Atacama Large Millimeter Array may be able to isolate the transition from dust to free-free/synchrotron emission for sources of this type and allow more reliable redshift estimates.
3. Investigating the role of ice emission locally could be taken up using SOFIA or Spitzer.
4. Very low resolution \( H \)-band spectroscopy might test the possibility of a \( \text{Ly}_\alpha \) blackout for HDF 850.1.
5. Molecular studies which target \( H_2O \) and OH maser emission may give definite redshifts using a new generation of radio telescope arrays even if the continuum is below detection limits.

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