Reionization on ice

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Abstract. The case for substantial far infrared ice emission in local ultraluminous infrared galaxies, expected based on the presence of mid-infrared ice absorption in their spectra and the known far infrared optical properties of ice, is still largely unsupported by direct observation owing to insufficient far infrared spectral coverage. Some marginal supportive evidence is presented here.

A clear consequence of far infrared ice emission is the need to extend the range of redshifts considered for submillimeter sources. This is demonstrated via the example of HDF 850.1.

The solid phase of the ISM during reionization may be dominated by ice, and this could lead to the presence of reionization sources in submillimeter source catalogs. Submillimeter sources not detected at 24 μm in the GOODS-N field are examined. Two candidate reionization sources are identified at 3.6 μm through possible Gunn-Peterson saturation in the Z band.

1. Ice emission

The discovery of ice absorption features in the spectra of ultraluminous infrared galaxies (ULIRGs; Spoon et al. 2002; Imanishi & Maloney 2003; Imanishi, Dudley & Maloney 2006) implies that ice is emitting in the far infrared (FIR). The observational consequences are determined by the portion of FIR emission that is owing to mid-infrared absorption (often the majority) and the ratio of mantle-to-core volumes of the emitting dust as well as the FIR optical depth. For ULIRG FIR dust temperatures one expects the broad 150 μm phonon mode (Berti et al. 1969; Curtis et al. 2005) of ice to modify the FIR spectral energy distribution (SED) through emission. An example is given in Fig. 1a.

This changes at the higher dust temperatures required at higher redshift where the CMB temperature exceeds (optically thin) ULIRG temperatures. Then, shorter wavelength ice features are more important to SED modification. Fig. 1b. shows HDF 850.1, the brightest submillimeter source in the Hubble Deep Field, plotted against an ice emission model. The redshift, z = 12.6, is 13 confidence intervals beyond the estimate of Dunlop et al. (2004): z = 4.1. Thus, ice emission could greatly broaden the range of redshifts that need to be considered for submillimeter sources. Fig. 3a. shows the expected 850 μm brightness of sources with the luminosity of ULIRG IRAS 00188-0856 if they are similar to Arp 220 (long dashed line), have substantial ice and a temperature of 30 K (solid line), or are similar to the model shown in Fig. 1b. (50 K; short dashed line). It is notable that the last model selects for z = 13.

2. What is the early ISM like?

When metals are first released into the interstellar medium the oxygen-to-carbon ratio is high and the 56Ni production is frequently low. For a 186 M⊙ progenitor
Fig. 1a. Two fits for the FIR SED of ULIRG IRAS 14348-1447 are shown. The dashed line reproduces the fit given by Klaas et al. 2001 and has a 100 µm optical depth of 5 and $\beta = 2$ while the solid line is an ice mantle-core emission model taken from Aannestad (1975). The broad feature centered near 150 µm is hinted at in the ISOPHOT data though one fit is not better than the other. This source shows 6 µm absorption e.g. Charmandaris et al. (2002).

Fig. 1b. Data from Dunlop et al. (2004) plus a new Z band limit (Dudley et al. 2006; filled circles; lensing corrected) are plotted together with new Spitzer GOODS data for the lensing galaxy (filled diamonds; relative scale). Solid lines show an ice emission model and a starburst model (Leitherer et al. 1999). Dashed lines and the shaded region represent evolution of the lensing elliptical galaxy e.g. Athey et al. (2002).

(90 M$_\odot$ core) the yield ratios are O:Si:C:S:56Ni=123:29:15:10:1 by number (Heger & Woosley 2002) so that the onset of dust formation may be rapid and occur in an oxygen rich environment. If grain temperature is determined by kinetic and chemical interactions when the mainly oxygen ejecta mix with the surrounding mainly hydrogen atmosphere (Baraffe, Heger & Woosley 2001) for example, rather than by ongoing radioactivity, grain surface and gas phase chemistry might lead to the condensation of ice mantles at temperatures high enough to lead to the formation of crystalline rather than amorphous ice such as is observed to occur in some evolved stars.

If all or most oxygen enters the solid state, the volume of ice at this early phase would be larger than the volume of more refractory material. Further, if the injection of such material is needed to facilitate the formation of the generation of stars that is proposed to be 4 Gyr old at $z = 1.5$ (Jimenez et al. 2000) or $>2$ Gyr old at $z = 2.5$ (Stockton et al. 2004) then the formation interval, if set by this initial enrichment, may be brief enough that a substantial fraction of stars are found simultaneously within their natal envelopes which may yet contain crystalline ice.

3. Does SCUBA see to reionization?

The positional error circles shown in Fig. 2 for SCUBA 850 µm sources cataloged by Wang et al. (2004) are remarkable because so many of them are empty at 24 µm. Six are definitely clear of obvious sources and an additional four (sources 27, 28, 41 and 44) are borderline. If every SCUBA source has a 24 µm counterpart, we expect this situation to occur 2.25 times using 2σ radii error circles. And, that is in the absence of coincidental association. So, some number greater than zero of the 850 µm sources may not have 24 µm counterparts.

At the sensitivity of the GOODS MIPS image that implies $z > 4$ using ULIRG templates. Chapman et al. (2005) argue that radio non-detected sub-
millimeter sources have a similar redshift distribution to those radio detected sources for which they have obtained optical spectra. However, their argument depends on the SEDs of the sources being similar to normal galaxies, and Fig. 3b. shows that this may not be the case. So, the MIPS data together with a reanalysis of sources with known redshifts suggest a higher redshift population could be present in submillimeter catalogs.

We find sources in the 24 µm blank fields for HDFGOODS 850-8 and 850-14 which are similar to HDF 850.1 in that they are detected in the "NIR" (3.6 µm) but not at I or Z band (Fig. 4). \( I - [3.6] > 5 \) and 4.5 (Vega) respectively. Should ice play the role suggested in Fig. 1b. in these sources, making them detectable at 850 µm but not too luminous to be precursors of the known old elipticals at \( z = 1.5 \) and 2.5, then these could be reionization sources. If Gunn-Peterson saturation explains the Z band non-detections then the redshifts of
Fig. 4. Spitzer IRAC 3.6 μm images for the fields of HDFGOODS 850-8 and 850-14 are reproduced from Fig. 2 together with Hubble ACS Z and I band images. The 3.6 μm sources indicated with the yellow arrows are absent at the shorter wavelengths. Green contours are 3.6 μm data.

these sources would be greater than 7 and thus larger that the $z \sim 6$ onset of the Gunn-Peterson trough (Fan et al. 2004) while the redshift of last star formation is $z \sim 13$ for the old ellipticals in a WMAP cosmology (Spergel et al. 2003). This coincides with the redshift range for reionization estimated by Kogut et al. (2003). These sources may prove easier to observe than HDF 850.1 owing to the absence of a lens.

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