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ORIGINAL ARTICLE

Redshift distribution of the submillimeter extragalactic background light

Is ALMA going to see many high-redshift galaxies?

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Abstract The submillimeter (submm) extragalactic background light (EBL) traces the integrated star formation history throughout the cosmic time. Deep blank-field 850 µm and 1.4 GHz surveys and optical follow-up have been only able to determine the redshift of ∼20% of the submm EBL. The majority (80%) of the submm EBL is still below the confusion and sensitivity limits of current submm and radio instruments. We break through these limits with stacking analyses on our deep 850 µm image in the GOODS-N and find that the submm EBL mostly comes from galaxies at redshifts around 1.0. This redshift is much lower than the redshift of $z = 2$–3 previously implied from radio identified submm sources. This result significantly decreases the number of high redshift galaxies that may be seen by ALMA.

Keywords Submillimeter · Extragalactic background · Galaxy · ALMA

1 Introduction

The extragalactic background light (EBL) is an integrated measure of the history of the luminous energy production of the universe from both star formation and blackhole accretion. Directly emitted light is seen in the X-ray, UV, and optical, whereas dust reradiated energy appears in the far-infrared (FIR) and submillimeter (submm). The FIR and submm EBL measured by *COBE* is comparable to the optical EBL, showing that the submm wavelength is extremely important for understanding the evolution and formation of galaxies and active galactic nuclei. Further observations of the resolved submm EBL sources and X-ray observations (Alexander et al. 2003) suggest that these sources are mostly star forming galaxies and active galactic nucleus contribution is relatively small. In addition, the strong negative K-correction of the submm thermal spectra makes this waveband a very sensitive probe for high-redshift dust emission, although this negative K-correction alone does not necessarily make the observed submm sources a high-redshift population.

ALMA, as the most important next generation instrument in the submm wavelength, will provide the sensitivity and resolution for studying galaxy evolution at a great depth by observing the submm EBL sources. It will also have the potential of discovering high-redshift ($z > 4$) dusty galaxies that were previously missed by optical and near-infrared (NIR) surveys, if such a high-redshift population exists. In this paper we briefly summarize the previous understanding of the redshift distribution of the submm population and present our recent work on this topic. We also discuss the implication of our work to future ALMA surveys of high-redshift galaxies.

2 Redshift distribution of submillimeter sources

2.1 Bright SCUBA sources

Confusion limited blank-field SCUBA surveys have resolved ∼20%–30% of the submm EBL into point sources brighter than ∼2 mJy at 850 µm (hereafter bright SCUBA

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sources). Approximately 60% of these bright sources have radio counterparts at 1.4 GHz and their locations can be accurately determined by radio interferometry. Optical and near-infrared spectroscopy of radio identified bright SCUBA sources shows a redshift distribution of $z \sim 2$–3 (Chapman et al. 2003; Swinbank et al. 2004; Chapman et al. 2005). Radio-submm photometric redshifts of radio identified SCUBA sources generally also provide a similar redshift range (Barger et al. 2000; Ivison et al. 2002). These results show that the bright SCUBA sources are a high-redshift population. Furthermore, a common interpretation of the bright sources without radio counterparts is even higher redshifts, because of the positive K-correction in the radio.

Nevertheless, it is important to realize that the radio identified SCUBA sources only contribute at most $30\% \times 60\% = 20\%$ to the total submm EBL. The majority 80% of the submm EBL is either below the confusion limit of current submm instruments, or below the sensitivity limit of current radio interferometers. The redshift distribution of the fainter submm EBL sources does not necessarily match that of the bright sources, and is essentially unknown.

2.2 Stacking analyses on faint submm sources

Submm sources fainter than the confusion limit of SCUBA can be statistically detected with a stacking technique if there is prior information about their locations. In our most recent work (Wang et al. 2006, 2007) we performed stacking analyses on our 110 arcmin^2 GOODS-N SCUBA map (Wang et al. 2004) using galaxy samples selected from ground-based deep NIR images and ultradeep *Spitzer* IRAC images (GOODS *Spitzer* Legacy Science Program). The galaxy samples contain ~3000 sources with very complete redshift information (spectroscopic and photometric). We found that a combination of >2 μJy K_s band sources and >2 μJy 8.0 μm sources picks up the largest amount of 850 μm flux. By averaging the measured 850 μm fluxes at the locations of the K_s + 8.0 μm galaxies, we detected a surface brightness of 29.3 ± 2.6 Jy deg^{-2} at 850 μm, corresponding to ~67%–95% of the total 850 μm EBL measured by *COBE* (31 Jy deg^{-2} Puget et al. 1996, or 44 Jy deg^{-2} Fixsen et al. 1998). This large fraction of detected submm EBL is a substantial improvement over the result from just bright SCUBA sources. We also detected a 1.4 GHz EBL of 1.117 ± 0.026 Jy deg^{-2} and a 24 μm EBL of 6.42 ± 0.12 Jy deg^{-2} with the same stacking technique.

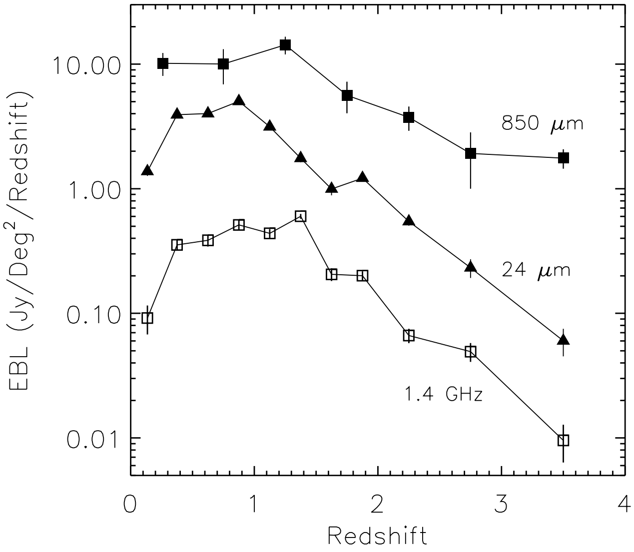

Fig. 1 Contributions to the 850 μm, 24 μm, and 1.4 GHz EBLs (in Jy deg^{-2} *per redshift*) vs. redshift. All the three EBLs are measured from the 2 mJy K_s + 8.0 μm sample. The total amounts of redshift identified EBLs are 24.7 ± 2.4, 5.8 ± 0.1, and 0.763 ± 0.024 Jy deg^{-2} at 850 μm, 24 μm, and 1.4 GHz, respectively. Note that all EBLs peak at $z \sim 1.0$. The slope of the submm EBL at $z > 1.5$ is much shallower because of the negative K-correction in the submm

Moreover, by grouping the NIR galaxy sample with their redshifts and optical/NIR spectral energy distributions (SEDs), we found that most of the detected submm EBL comes from galaxies with intermediate class SEDs (Wang et al. 2006). Among the detected 29.3 Jy deg^{-2} 850 μm EBL, 24.7 Jy deg^{-2} comes from redshift identified sources. The unidentified sources contribute 4.6 ± 0.9 and 0.35 ± 0.01 Jy deg^{-2} to the 850 μm and 1.4 GHz EBL, respectively, and are dominated by just couples of radio bright (>300 μJy) but optically faint sources. We show the EBL contributions vs redshift in Fig. 1, derived from the redshift identified sources. As shown in the figure, most of the submm EBL comes from redshifts around 1.0. This result suggests that the faint submm EBL sources and the bright SCUBA sources are two different populations at different redshifts. (Further analyses in their 850/24 μm colors also show that their dust temperature properties are different, Wang et al. 2007.) While this result fits into the popular scenario of "cosmic downsizing," it is still somewhat surprising, and it has to be tested with the current dataset and with future observations.

2.3 Tests on the stacking results

To ensure that the stacking results are unbiased, we performed various tests on our data. Among the most important ones, we measured 850 μm fluxes at random positions and found the stacking fluxes are consistent with zero. This zero sum is a direct result of the two negative 50% sidelobes of the SCUBA jiggle map. It shows that the low angular resolution of the SCUBA map does not produce a confusing flux that biases the stacking result and only a real correlation between the NIR sample and the submm sources can provide a non-zero stacking flux. We also repeated the same stacking analyses on the 1.4 GHz radio image (Richards 2000) and 24 μm image of GOODS-N, and found that the detected radio and 24 μm EBL shows consistent SED class distribution (Wang et al. 2006) and redshift distribution (Fig. 1). These radio and 24 μm measurements provide a strong support to the above submm result since they come from maps of totally different angular resolutions and noise properties.

Although our stacking results seem to be robust, further tests on the low-redshift origin of the submm EBL have to be carried out with new and independent observations before ALMA comes online in order to provide critical inputs to ALMA observations. One possible test is to measure the redshift distribution of radio-identified faint submm sources lensed by clusters. These lensed, faint sources are below the normal confusion limit of SCUBA. They can provide a direct comparison with the statistically detected faint submm sources in the stacking analyses. Although lensing surveys may favor high redshift objects, good lensing geometry models can help to account for this bias effect.

2.4 Cosmic star formation history

With the measured redshift distribution of the submm and radio EBL, we can infer the cosmic star formation history (i.e., comoving star formation rate density, SFRD, as a function of redshift) using the standard star formation rate formula $\dot{M} = 1.7 \times 10^{-10} L_{\mathrm{IR}}/L_{\odot}$ (Kennicutt 1998). The infrared luminosities can be converted from either 850 μm fluxes or radio fluxes. The 850 μm conversion is probably relatively robust only for bright SCUBA sources since they have similar dust properties. The radio conversion is more reliable for the entire sample, given the tight correlation between radio power and infrared luminosity in star forming galaxies. The results are shown in Fig. 2. It is clear that although bright SCUBA sources have a redshift distribution strongly peaked at $z = 2$–3, the entire submm/infrared SFRD is relatively flat at $z > 1$.

3 Discussion

Our successful stacking detection of the 850 μm EBL can be attributed to the properties of the $K_s + 8.0$ μm sample. The rest-frame K_s band has relatively less extinction and is just slightly redder than 1.6 μm, where there is an opacity minimum in stellar atmosphere. Therefore the K_s band is very sensitive to slightly redshifted and dust extinguished stellar emission. Moreover, the 8.0 μm band directly picks up the blue end of the thermal dust emission and the strong PAH features from star forming galaxies. Consequently, sources selected at these two wavebands are highly correlated to the star forming, dusty submm population. On the other hand, these two wavebands may be biased against high redshift sources, as they start to miss the peaks of the stellar and dust spectra at $z > 1$. It is thus possible that a significant portion of the redshift unidentified submm EBL comes from redshifts greater or much greater than 1.0.

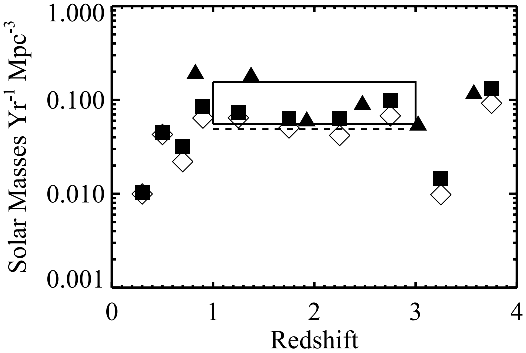

Fig. 2 SFRD vs. redshift (Wang et al. 2006). The *filled squares* show the SFRD derived from the radio EBL. The *open diamonds* show the same results when sources with 2–8 keV luminosities $>10^{42}$ erg s^{-1} (sources containing active galactic nuclei) are excluded. The *filled triangles* show the SFRD computed using the 850 μm EBL. The *rectangular region* denotes the SFRD from the missing submm EBL that is not accounted for by our NIR sample, assuming that it lies in the redshift interval $z = 1$–3. The range corresponds to the uncertainty in the total 850 μm EBL

Nevertheless, our stacking analyses place approximately 17 Jy deg^{-2} of the submm EBL at $z < 1.5$, and leave 7 or 20 Jy deg^{-2} of the submm EBL redshift unidentified, depending on which of the *COBE* EBL measurements is adopted (Puget et al. 1996; Fixsen et al. 1998). While the exact amount of unidentified submm EBL and its redshift distribution is still open, the above results already dramatically lower the number of high-redshift submm emitting sources that ALMA may see. Because of this, any ALMA survey that targets on discovering high-redshift ($z > 4$) sources has to increase the area coverage. For example, if we assume the maximum missing EBL of 20 Jy deg^{-2} and place 20% of it at $z > 4$, we find a source density of 8×10^3 deg^{-2} for a typical source flux of 0.5 mJy (Cowie et al. 2002). This corresponds to 0.15 sources per ALMA field of view. To detect a significant sample of 100 of such sources at 850 μm at 10 σ, approximately 300 hour of integration is needed.

The above simple and optimistic integration time estimate does not yet include any effort that is needed to identify these high redshift submm sources. (As an example, multi-wavelength submm color selection of high redshift dust emission will require at least a few times more observing time.) The great difficulty of identifying them is hinted by the simple fact that they are still missed by our stacking analyses. This missing EBL was not picked up by even the deepest *Spitzer* 3.6–24 μm imaging and 10-m class ground-based optical imaging. After the submm EBL is fully resolved by ALMA, a significant amount of the ALMA sources will not have optical and NIR counterparts, or the counterparts will be too faint for spectroscopic follow-up with current ground-based and space-based instruments.

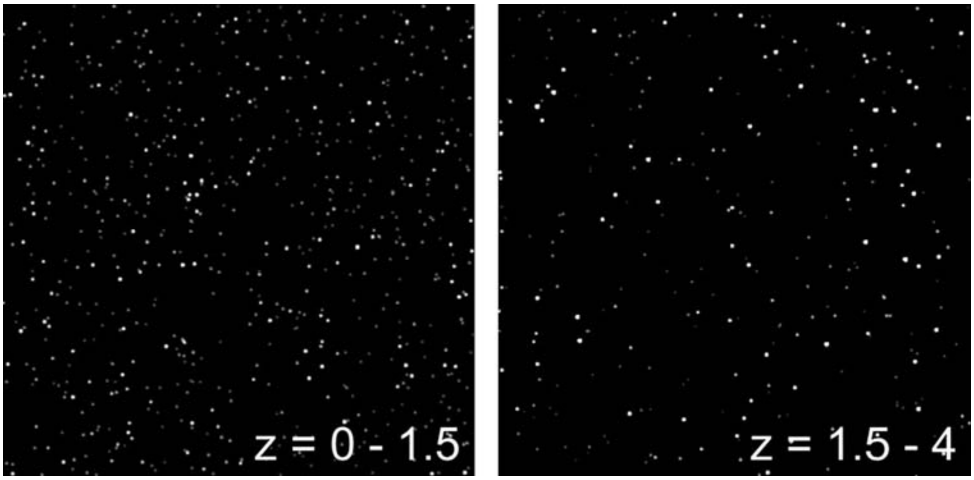

Fig. 3 Simulated 100 arcmin^2 ALMA maps (with a degraded resolution) of nearly fully resolved 850 μm EBL. Here we assume: (1) our bright-end number counts from SCUBA blank-field surveys (Wang et al. 2004); (2) our faint-end number counts from SCUBA lensing cluster surveys (Cowie et al. 2002); (3) the redshift distribution of the submm EBL in Fig. 1; and (4) the fact that bright SCUBA sources almost only appear at $z > 1.5$ (Chapman et al. 2003, 2005). Under the above assumptions, sources at $z < 1.5$ dominate the total submm source number and the total submm EBL. At $z > 1.5$, the submm population is dominated by a relatively small number of bright SCUBA sources. This picture does not account for the EBL still missed by our stacking analyses, which may be at $z > 1.5$

They may be as well too faint for the EVLA to detect their synchrotron radiation, and for wide-band receivers on large single-dish telescopes to detect the redshifted CO lines. It is almost certain that in order to fully understand the submm EBL sources, next generation instruments in all wavebands from optical to millimeter are critically needed.

4 Summary

Bright submm sources identified in the radio contribute ~20% to the total submm EBL, and are at redshifts between 2 and 3. Fainter submm sources, which account for the majority of the submm EBL and cosmic star formation, can be detected with a stacking technique and appear to have a redshift distribution peaked at 1.0. This implies that most of the submm EBL sources resolve by ALMA will be low-redshift sources. To summarize this paper, in Fig. 3 we present simulated ALMA maps of submm EBL sources at $z < 1.5$ and $z = 1.5$–4.

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