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PRIMEVAL GALAXIES IN THE SUB-MM AND MM

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ABSTRACT. *Although the results of COBE's FIRAS experiment*[1] *constrain the deviation in energy from the CMB blackbody in the 500-5000μ range to be* $\Delta E/E_{cmb} < 0.005$, *primeval galaxies can still lead to a brilliant sub-mm sky of non-Gaussian sources that are detectable at 10″ resolution from planned arrays such as SCUBA on the James Clerk Maxwell Telescope and, quite plausibly, at sub-arcsecond resolution in planned mm and sub-mm interferometers. Here we apply our hierarchical peaks method*[2] *to a CDM model to construct sub-mm and mm maps of bursting PGs appropriate for these instruments with minimum contours chosen to correspond to realistic observational parameters for them and which pass the FIRAS limits.*

Where does the waste heat from galaxy formation lie? The nuclear energy output of stars with efficiency ϵ_{nuc} (which is less than 0.004, but not by very much for massive stars) radiating at redshift z_* with an abundance Ω_* relative to the CMB is $\Delta E_*/E_{cmb} \sim 0.03\ (\Omega_* h^2/10^{-3})[(1+z_*)/5]^{-1}\ \epsilon_{nuc}/0.004$. The radiant energy release from stars which eject a mass $Z_{ej}M$ in metals when they undergo supernova explosions is limited by the metal fraction Z they contribute to a gas of density Ω_{gas}, $E_{preSN*}/E_{cmb} \sim 0.0008$ $(Z/10^{-3})(\Omega_{gas}h^2/10^{-2})$ $[(1+z_*)/5]^{-1}$ $(Z_{ej}/0.2)$ $(M/20\,M_\odot)^{0.5}$. Radiation generated by mass accreting onto black holes with an efficiency ϵ_{acc}, typically taken to be about 0.1 for quasar models, delivers energy $\Delta E_{BHacc}/E_{cmb} \sim 0.0008(\Omega_{BHacc}h^2/10^{-6})[(1+z_{acc})/5]^{-1}\ \epsilon_{acc}/0.1$. We expect $\Omega_*\epsilon_{nuc}$, $Z\Omega_{gas}$ and $\Omega_{BHacc}\epsilon_{acc}$ to be significantly larger than the normalizations given, and quite possibly in conflict with the FIRAS limits.

One way out of the FIRAS dilemma is to have no dust of course, so the radiation is just redshifted. It would then lie in the near infrared and the constraints are still not very restrictive there, even from COBE's DIRBE experiment, which is plagued by difficult foreground subtractions before it can get to the residual cosmological signal. Although it may well turn out that extensive dust production in early galaxies covers only a small fraction of its overall scale ($z \sim 2$ 'Wolfe disks' being relatively metal poor), so most lines of sight to high redshift do not pierce through a significant optical depth of dust (*c.f.* ref. 3), we would be surprised if there were no analogue of the dust-shrouded starburst phenomenon in galactic cores at high redshifts. To allow a large energy generation with dust, one could make the grains hot: for example, 70K dust delivers its peak at about $50\mu(1+z_{gf})$ which might just have missed the FIRAS band for a galaxy formation redshift $z_{gf} \lesssim 7$. However, moderate energy releases which satisfy the FIRAS constraint can still lead to interesting sub-mm skies as we now show.

To focus the discussion, we give a concrete example using the CDM model with amplitude factor $\sigma_8 = 0.67$ ('bias' factor $\sigma_8^{-1} = 1.5$). We first must identify primeval galaxy sites and secondly choose how much energy is produced and in what wavebands. Although we think we can be reasonably confident about the first stage, by using the hierarchical peaks method[2] for identifying galaxy halos at these high redshifts, unfortunately there are too many parameters at our disposal to be definitive about how the energy is released in galaxy formation, even in a supposedly well defined model like CDM. We constructed a 2-component peak model (using 2 filter scales) consisting of fiducial dwarf galaxies (mass in baryons $\sim 3\times10^9\,M_\odot$ and halo radius ~ 18 kpc) and 'normal' galaxies (mass in baryons $\sim 4\times10^{10}\,M_\odot$ and halo radius ~ 42 kpc).

The dust was assumed to be of a 'normal' (Galactic) variety, distributed in randomly oriented exponential disks with e-folding radii $r_e = 1.8$ kpc and 4.2 kpc respectively, with a dust-to-baryon fraction in the galaxies of 0.2%, and was assumed to be emitting with a λ^{-1} opacity law at a characteristic temperature of 30K (leading to an intensity peak at $\sim 600\mu$). The total luminosities are then star-burst level, $\sim 10^{44}S$ erg/s and $\sim 10^{45}S$ erg/s, respectively, where S is a scale factor that we are free to choose as long as we satisfy the FIRAS constraint; *e.g.*, S increases linearly with the dust-to-baryon ratio and is quite sensitive to dust temperature changes. (If $S \approx 10$ then the normal galaxies would all be emitting at an Arp 220 level).

We assume these primevals were bursting between their formation (but do not include any generation earlier than $z = 6$) and an arbitrary cutoff redshift we chose to be $z = 4$. With these parameters, the energy in the background from these objects would be $\Delta E/E_{cmb} \sim 0.01S$, hence $S \lesssim 1/2$ is required. The metallicity that results from such luminosities over such times is not a great restriction on these models.

The maps in Figure 1 correspond to SCUBA, a submm interferometer and a mm interferometer. Experiments that have already looked for PGs in the mm, at IRAM[4] (λ=1.3mm, 11″ *fwhm* beam), and in the submm, at JCMT[5] (λ=760μ, 18″ *fwhm* beam), have placed 95% upper limits on the strength of *rms* intensity fluctuations of 0.9 mJy/beam and 12 mJy/beam, respectively. Although these limits can be used to constrain the source density and clustering of some PG models that satisfy FIRAS limits,[3,5] they do not significantly constrain the starburst models considered here. SCUBA, which should come on line within a year, will have *much* higher sensitivity than the Church *et al.* JCMT experiment.[5] Indeed, it is clear from Figure 1 that SCUBA-like instruments will be invaluable for identifying promising PG candidates, but will be confusion-limited because of the beam size. Higher resolution studies will be essential for unraveling the nature of the sources. Sub-mm interferometers appear to be the most promising in terms of signal, but how strongly the atmosphere will limit the sensitivity is not well known at this early stage of their development. Interferometers at mm wavelengths can achieve the assumed sensitivities of Fig. 1(c), but the extrapolation of the flux into the mm depends upon the opacity law and the distribution of dust temperatures.

References

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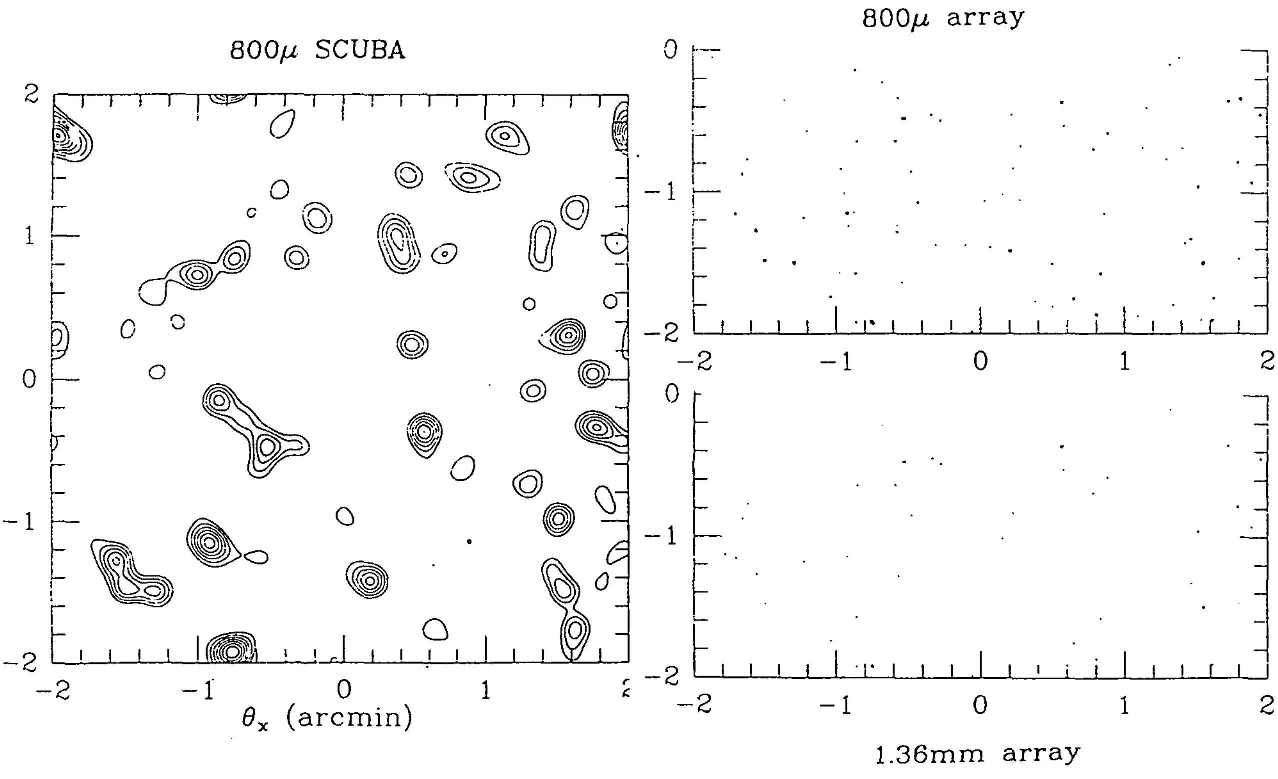

Figure 1. *(a) A 4′ × 4′ contour map for dust-emission from primeval galaxies at $z \sim 5$ convolved with a 12″ beam appropriate for the 855μ 37-pixel SCUBA array. The minimum contour is 1000S μJy/beam and subsequent contours increase linearly in 250S μJy/beam steps. SCUBA has a 2′ × 2′ FOV and is expected to achieve 470 μJy/beam at the 1σ level in just one hour of integration. (b) shows the lower half of the same map seen with a 1″ beam with 250S μJy/beam contours for an 800μ sub-mm array. (c) shows the lower half for a 0.86″ beam with 200S μJy/beam contours for a 1.36 mm array, which can be reached in ~ a day with the upgraded OVRO mm interferometer.*