Intensity Mapping of Fine Structure Line Emission as a Probe of Large Scale Structure and the Evolving ISM in Dusty, Star-Forming Galaxies at Moderate Redshift

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ABSTRACT

We explore the possibility of studying redshifted far-IR fine-structure transitions through cosmic time using 3-dimensional power spectra obtained with an imaging spectrometer. The intensity mapping approach measures the spatio-spectral fluctuations due to line emission from all galaxies, including those well below the individual detection threshold. With assumptions about large-scale structure, the large-scale fluctuations measure the total volume emissivity in a given transition, with redshift information naturally encoded. We consider as specific examples the possibility of studying redshifted [O I] 63 μm and [Si II] 35 μm with the SAFARI instrument aboard *SPICA*. While envisioned SAFARI surveys will only detect the brightest galaxies individually, the fluctuation signal from the aggregate population is detected with high significance: cumulative SNR of order ~100 for both the total and shot noise power spectra, and order ~10 for the clustering power spectrum from surveys sketched in this proceedings article.

1. ABOUT INTENSITY MAPPING

Intensity mapping is a *statistical* observation of emission line intensity fluctuations in a volume of the Universe, yielding a data cube in which galaxies need not be either spatially or spectrally resolved. Atomic (Visbal & Loeb 2010; Gong et al. 2012) and molecular (Lidz et al. 2011) transitions—such as the 21 cm spin flip transition from H$^{\text{o}}$, CO (2–1), and [C II] 158 μm—have been investigated as candidates for line intensity mapping experiments during the Epoch of Reionization. Of these, the neutral hydrogen case is undoubtedly the most developed in terms of its standing in the literature and in the experimental arena (e.g., PAPER, MWA, and LOFAR), and so interest in measuring other line power spectra has primarily erupted as a means to complement the 21 cm studies at high redshift via the cross-correlation.

Here we examine, however, the feasibility and value of measuring the 3-dimensional (3D) auto-power spectra of infrared fine structure (FS) emission lines at low to moderate redshifts, specifically between $z = 0.5$ and $z = 3$. Two intrinsic qualities of the intensity mapping technique—namely, the ability to map large areas of sky while encoding redshift information in the spectral dimension, and the sensitivity to galaxies which are below the threshold for individual detections of current and future instruments—guide our discussion in what follows.

2. PREDICTIONS FOR FS LINE POWER SPECTRA: AN EMPIRICAL APPROACH

The complete 3D auto-power spectrum of a given FS line (denoted by the subscript i) as a function of wavenumber k and redshift, $P_{i,i}(k, z)$, can be separated into power from the clustering of galaxies, $P_{i,i}^{\mathrm{clust}}(k, z)$ and a Poisson term, $P_{i,i}^{\mathrm{shot}}(z)$. We compute the full nonlinear dark matter power spectrum, $P_{\delta,\delta}(k, z)$, with the widely used, publicly available code HALOFIT+ (Smith et al. 2003). The clustering component of the line power spectrum is then written as

$$P_{i,i}^{clust}(k, z) = \bar{S}_i^2(z)\bar{b_i}^2(z)P_{\delta,\delta}(k, z). \tag{1}$$

This expression implicitly assumes that the fluctuations in line emission trace the matter power spectrum with some average bias, $\bar{b}_i(z)$.

The mean intensity $\bar{S}_i$ and shot noise power $P_{i,i}^{\mathrm{shot}}(z)$ are, in turn, calculated using the IR luminosity function, $\Phi(L_{\mathrm{IR}}, z) = \frac{\mathrm{d}N(L_{\mathrm{IR}},z)}{\mathrm{d}V\,\mathrm{d}L_{\mathrm{IR}}}$:

$$\bar{S}_{\mathrm{i}}(z) = \int_{L_{\mathrm{IR,min}}}^{L_{\mathrm{IR,max}}} \mathrm{d}L_{\mathrm{IR}}\Phi(L_{\mathrm{IR}}, z)\frac{f_i L_{\mathrm{IR}}}{4\pi D_L^2} y_i D_A^2 \tag{2}$$

$$P_{i,i}^{\mathrm{shot}}(z) = \int_{L_{\mathrm{IR,min}}}^{L_{\mathrm{IR,max}}} \mathrm{d}L_{\mathrm{IR}}\Phi(L_{\mathrm{IR}}, z)\left(\frac{f_{\mathrm{i}} L_{\mathrm{IR}}}{4\pi D_L^2} y_i D_A^2\right)^2, \tag{3}$$

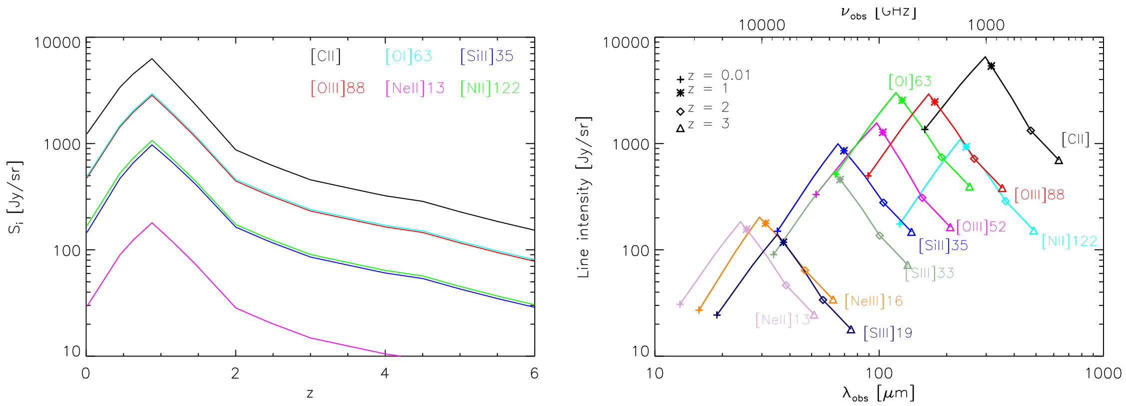

Figure 1. *Left:* Predicted mean intensity of FS line emission plotted versus redshift, and *Right:* observed wavelength (and frequency).

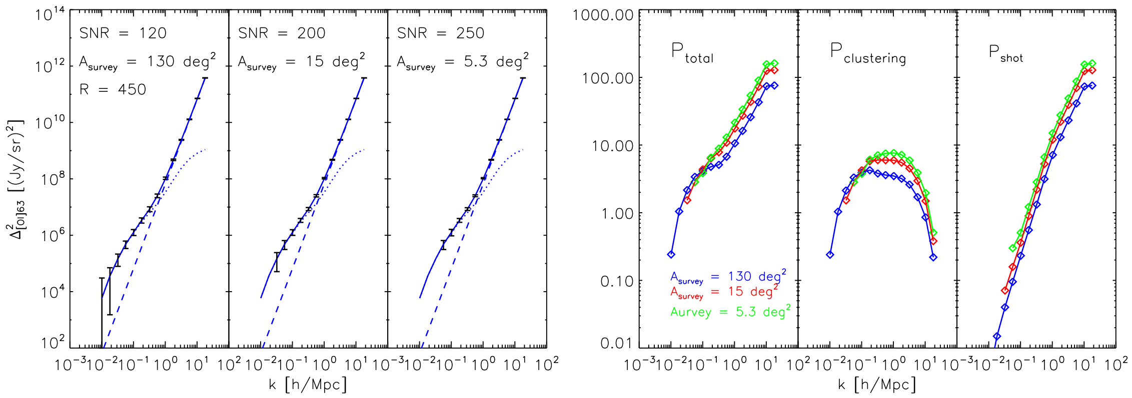

Figure 2. *Left:* Predicted [O I] 63 μm power spectrum. Power from clustering and shot noise are shown as the dotted and dashed curves, respectively (see text for survey parameters). *Right:* SNR vs k for the total, clustering, and shot noise power.

where f_i is the fraction of IR luminosity emitted in line i, y_i is the derivative of the comoving radial distance with respect to the observed frequency, i.e. $y_i = d\chi/d\nu = \lambda_{i,rest}(1+z)^2/H(z)$, D_L is the luminosity distance, and D_A is the comoving angular distance. To make explicit predictions, we use the IR luminosity function of Béthermin et al. (2011) and line ratios of Spinoglio et al. (2012). We note that other choices are possible, but the former accurately reproduces the known continuum number counts of galaxies, and the latter summarizes the current state of knowledge of FIR lines from local surveys. The resulting $\bar{S}_i$ for a variety of FS lines are plotted in Figure 1 as functions of redshift and observed frequency. $\bar{S}_i$ vs $\lambda_{\rm obs}$ can be interpreted as identifying the dominant source of fluctuations, according to our model, at a given wavelength. It will be necessary to distinguish between the target line and contaminants from different redshifts which nonetheless contribute power at the observed frequency. Visbal & Loeb (2010) showed how the cross spectra can be used to differentiate between a target line and a so-called "bad line", since emission at different redshifts will be spatially uncorrelated.

An example power spectrum for the bright line [O I] 63 μm, observed at $z = 1.5$, is shown in Figure 2 (*left panel*). For this calculation, total observing time is fixed at 450 hours, and survey size is varied from 5.3 deg^2 to 130 deg^2, corresponding to a time per pixel of 0.09 to 0.003 hr, respectively. We calculate error bar estimates and Signal-to-Noise Ratio (SNR) for the power spectrum by assuming a spectrally flat noise power spectrum, so that the noise power in each pixel, P_N, is $\sigma_N^2 \frac{V_{\rm pix}}{t^{\rm pix}_{\rm obs}}$, where σ_N^2 is the instrument sensitivity (noise equivalent intensity, or NEI, in units of Jy sr^{-1} Hz$^{-1/2}$), $V_{\rm pix}$ is the pixel volume, and $t^{\rm pix}_{\rm obs}$ is the time spent observing on a single pixel. The variance of a measured k, $\sigma^2(k)$, is $\frac{(P_{i,i}(k,z)+P_N)^2}{N_{\rm mode}}$, where $N_{\rm mode}$ is the number of wavemodes that are sampled for a given k bin of some finite width. In calculating the power spectrum sensitivity, modes with line-of-sight component equal to zero are discarded, since these will likely be compromised by the necessity of continuum foreground subtraction. To demonstrate the feasibility of measuring galaxy clustering modes on the linear scale, the nonlinear scale, and the transition between the two regimes, we also present in Figure 2 (*right panel*) SNR on the power spectrum as a function of k. (Note that we use $\Delta_i^2 = k^3 P_{i,i}(k)/(2\pi^2)$ when plotting the power spectrum throughout this proceedings. In this notation, the factor k^3 cancels out the volumetric units in $P_{\delta,\delta}(k,z)$, and the integral of Δ_i^2 over d$\ln k$ equals the variance in real space.)

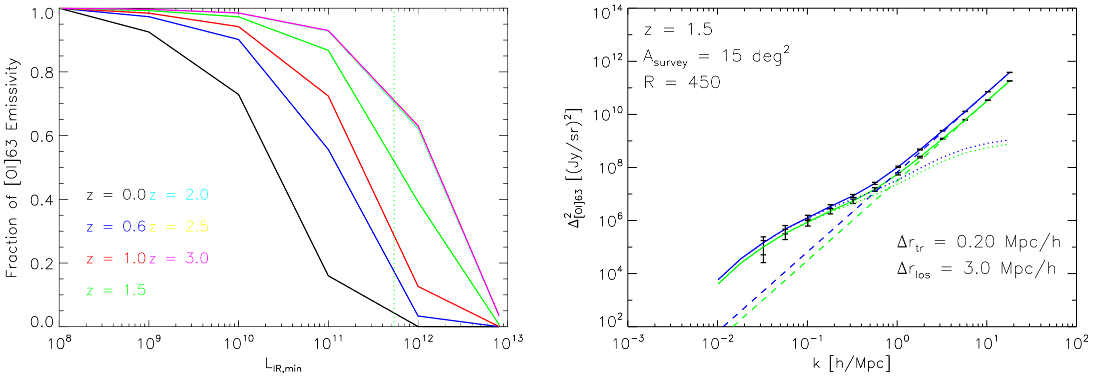

Figure 3. *Left:* Fraction of total [O I] 63 μm intensity as a function of lower limit in the luminosity function. The vertical green dotted line denotes the $5\sigma - 1$hr SAFARI sensitivity. *Right:* [O I] 63 μm power spectrum at $z = 1.5$ before (blue curve) and after (green curve) removal of SAFARI-detected sources.

3. UNIQUELY PROBING THE MAJORITY OF LINE EMISSION

Figure 3 (*left panel*) shows the fraction of total line intensity recovered by integrating Equation 2 with different $L_{\mathrm{IR,min}}$, calculated up to $z = 3$. ($L_{\mathrm{IR,max}}$ is fixed at 10^{13} $\mathrm{L}_{\odot}$.) Beginning at $z \approx 1.5$ for [O I] 63 μm and most other lines, it becomes apparent that $\gtrsim 50$ % of the line intensity from all extragalactic emitters at the same z will be unresolved by SAFARI. The problem is particularly dramatic at the upper end of the redshift range accessible to SAFARI. For example, $\lesssim 20$ % of the [Si II] 35 μm emission at $z = 3$ is recoverable at the $5\sigma - 1$hr level, whereas the total SNR on the [Si II] power spectrum is ~ 40 in a mere 45 hours of integration time on a 0.5 deg^2 field (figure not shown). However, it is important to note that the shot noise term is weighted more heavily toward high luminosity systems (cf. Equation 3).

On the other hand, the clustering power spectrum is sensitive to intensity fluctuations from the full range of normal to ULIRG-class systems because it is proportional to the first moment of the luminosity function (cf. Equation 2). In order to successfully extract $\bar{S}_1$ from the power spectrum, it is necessary to divide out $P_{\delta,\delta}(k, z)$ and $\bar{b}_1$. The confidence with which these are *a priori* known quantities becomes lower as k increases. For example, bias appears to be truly independent of luminosity only at large physical scales (Viero et al. 2013), indicating the need to map wide areas in order to derive $\bar{S}_1$. Returning, as an example, to the [O I] 63 μm power spectrum plotted in Figure 2, Figure 3 (*right panel*) now compares the predicted power from one such wide, 15 deg^2 survey (blue curve) with the predicted power that remains after galaxies above SAFARI's detection threshold have been excised from the survey (green curve); the total SNR on the clustering-only power spectrum remains high, decreasing from 15 to 10 as a result of the cut. This kind of wide area survey is prohibitively time-consuming for SAFARI if striving for individual detections, and at 0.09 hr per pixel for the 450 hr integration, SAFARI would not detect ~80 % of [O I] 63 μm-bright sources, according to our model. Thus, intensity mapping remains a viable means of measuring aggregate line emission as a function of redshift, and characterizing clustering of the low luminosity population.

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