SIMULATIONS OF THE FAR-INFRARED SKY

Paola Andreani[1,2], **Dieter Lutz**[2], **Albrecht Poglitsch**[2] **and Reinhard Genzel**[2]

[1]Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[2]Max Planck Institut für Extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany

Abstract

One of the main tasks of FIRST is to carry out shallow and deep surveys in the far-IR / submm spectral domain with unprecedented sensitivity. Selecting unbiased samples out of deep surveys will be crucial to determine the history of evolving dusty objects, and therefore of star-formation.

However, the usual procedures to extract information from a survey, i.e. selection of sources, computing the number counts, the luminosity and the correlation functions, and so on, cannot lead to a fully satisfactory and rigorous determination of the source characteristics. This is expecially true in the far-IR where source identification and redshift determination are difficult. To check the reliability of results the simulation of a large number of mock surveys is mandatory. This provides information on the observational biases and instrumental effects introduced by the observing procedures and allows one to understand how the different parameters affect the source observation and detection.

The project we are undertaking consists of (1) simulating the far-IR/submm surveys as PACS (and SPIRE) will observe, (2) extracting from these complete mock catalogues, (3) for the foreseen photometric bands selecting high-z candidates in colour-colour diagrams, and (4) testing different observing strategies to assess observational biases and understand how the different parameters affect source observation and detection.

Key words: Galaxies: formation; evolution; surveys – Missions: Herschel-FIRST

1. Why simulations?

Computer-aided modeling is becoming an essential tool in planning new experiments. For example, because of the cost of any space-based telescope, nowadays it is not even conceivable to plan a mission without first simulating the performances of the instruments and/or of the observing mode.

Simulations are key in assessing the reliability of the extracted information from a survey and defining a confidence level to the results for basically two main reasons:

- Uncertainties introduced by 'photometric' errors and the variance in the Spectral Energy Distribution (SED) of the sources make the nature of the problem intrinsically stochastic. Even taking account of the influence of the different SEDs in the computation of the absolute luminosity, the problem remains basically unsolved. For example, because of the effects of the photometric errors two measurements of the same flux and the same SED and redshift may be produced by objects of different absolute luminosity. This means that it is impossible to establish a one-to-one relationship between the observed flux and the absolute luminosity as a function of z and the SED.
- A wide assumption, which is often made because of its simplicity, is that the processes underlying a given physical phenomenon obey Gaussian statistics (and therefore linear). However, although as practical as this assumption could be, it is not applicable for most of the physical systems which, on the contrary, are expected to be characterized by nonlinear behaviours. In particular, studies of source properties in the far-IR imply the disentangling of the source emission and position from those of a much stronger background whose spatial structure is highly non-Gaussian.

2. Why Non-Gaussian Simulations?

The present main limitation of deep extragalactic and Galactic surveys is the noise due to (1) fluctuation of the IR cirrus emission from interstellar dust even at high Galactic latitudes and (2) source confusion in the beam. A detailed study of both these phenomena is mandatory before planning deep surveys with forthcoming IR space telescopes. Their nature is intrinsically non-Gaussian and to understand how these phenomena – as well as source clustering – affect source detection a different approach must be used.

2.1. IR Cirrus

The spatial structure of the IR cirrus at 100 μm as measured by IRAS was extensively studied by Gautier et al. (1992) and Abergel et al. (1996) . From a Fourier transform analysis of the brightness distribution, Gautier et al. found that the Power Spectral Density (PSD) of the brightness fluctuation at 100 μm follows a power-law func-

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tion of the spatial frequency with an index of about 3 below the spatial frequency corresponding to the IRAS beam size (about 0.25 arcmin $^{-1}$). They also found that the PSD is proportional to B_0^3, where B_0 is the mean brightness of the IR cirrus.

ISO observations carried out with the ISOPHOT camera show similar power-law spectra in bright cirrus regions extended to higher spatial frequencies ($\sim 1'$) (Herbstmeier et al. 1998) and different wavelengths. In high Galactic latitude fields Lagache & Puget (2000) find that at 170 μm the power spectrum has a shape of the form $\mathrm{P(k)} = 7.9^{+2.1}_{-2.7}(\mathrm{k})^{-3}$ Jy^2/sr but has a significant excess at spatial frequencies $f = 0.25 - 0.6$ arcmin^{-1}, which is attributed to fluctuations of unresolved extragalactic sources (see also Matsuhara et al 2000). ISOPHOT observations are limited by possible field-to-field fluctuations and by the fact that in some regions the spatial correlation length is larger than the typical ISOPHOT maps.

FIRST with its higher resolving power will probe regions down to a scale of a few arcseconds. At present the behaviour of the fluctuations at higher spatial frequencies can only be extrapolated and different scenarios will be simulated.

2.2. Source Confusion

Confusion arises because of the uncertain and varying contribution of flux density from the numerous unresolved faint sources that fall within each observing beam. It leads to a non-Gaussian distribution of random intensity fluctuations on the sky, whose properties depend on the details of both the shape of the counts and the clustering strength of the galaxies in the survey. Confusion becomes the dominant noise for any observations deeper than a certain limit, which generally corresponds to a density of sources in the sky that is greater than about 0.03 beam^{-1} (e.g. Condon 1974, Hogg 2001).

If cirrus noise shrinks to higher resolution as k^{-3}, confusion noise constitutes the main limitation to deep surveys over significant part of the sky.

3. Numerical Simulations

The aim is to reconstruct the extragalactic sky in the presence of Galactic background, instrumental noise and confusion.

At any given frequency ν, the total sky emission in a direction $\mathbf{x}$ is given by the superposition of the physical components, p, (see e.g. Hobson et al. 1999):

$$S_\nu(\mathbf{x}) = \sum_{i=1}^{N} B_\nu(|\mathbf{x}-\mathbf{x_i}|) \sum_p F_{\nu p} z_p(\mathbf{x_i}) + \psi_\nu(\mathbf{x}) + \epsilon \qquad (1)$$

where z_p is the signal from the p-th physical component, the corresponding total emission at the observing frequency ν is then obtained by multiplying z_p by the frequency response matrix $F_{\nu p}$ which includes the spectral behaviour of the components plus that of the instrument. This contribution has then to be multiplied with the beam profile, $B_\nu(\mathbf{x})$. ψ is the contribution to the noise from unresolved point sources and ϵ is the expected instrumental noise.

The survey simulation is more efficiently done by working in Fourier space since there we may consider each k-mode independently:

$$\mathbf{S} = \mathbf{Rz} + \psi + \epsilon \qquad (2)$$

where $R_{\nu p}(\mathbf{k}) = \tilde{P}_\nu(\mathbf{k}) F_{\nu p}$. Then simulations in real space are reconstructed via the inverse Fourier Transform.

This procedure implies that each physical component is independently simulated and then combined together via equation (1).

We briefly describe in the following how we build up the different terms in equation (1) (§ 3.1 and 3.2) and how the source signal can be extracted using the foreseen observing strategy (§ 4).

3.1. Mock galaxy catalogues

Our first aim is to reproduce the extragalactic sky. The approach we followed is as empirical as possible and uses a statistical analysis. It is generally called *Backward Evolution* (see e.g. Pearson 2001 and references therein) since it starts from the present epoch and tries to extrapolate the local (statistical) properties of galaxies to higher redshifts to predict how sources formed, behaved and evolved since their birth.

The statistical properties of the evolving underlying population of objects are inferred from the luminosity function (LF) and its evolution, the spatial distribution of sources via the angular correlation function, the integral and differential source counts and the integrated background due to the integrated emission from the unresolved sources.

The main steps of the flux diagram, built to reconstruct the extragalactic sky, are the following:

- An analytical expression for the *local luminosity function* at a given wavelength, $\Psi_\lambda(L,0)$, and its *evolution with time*, $\Psi_\lambda(L,z) = \Psi_\lambda(L,0) \cdot E(L,z)$, are assumed. Then a *number* of objects, proportional to the surface area of the survey, is randomly extracted.
- From the assumed family of galaxy SEDs *K-corrections* are computed. The relation between flux and luminosity is, in fact, given by:

  $$S_{\Delta\nu} = \frac{L_{\Delta\nu} K(L,z)}{4\pi d_L^2} \qquad (3)$$

  where in the frequency interval $\nu_1 - \nu_2$, the K-correction is defined as follows

  $$K(L,z) = \frac{\int_{\nu_1(1+z)}^{\nu_2(1+z)} L[\nu(1+z)]}{\int_{\nu_1}^{\nu_2} L(\nu)} \qquad (4)$$
- A *cosmological model* must be chosen to compute the volume element.

- the *volume of the survey* is computed according to the surveyed area and redshift depth. This volume is divided into *shells*, each one with a mean redshift z_m and a redshift thickness, Δz.
- According to the probability law given by the analytical form of the LF, a random value for the object *luminosity*, L_i, is extracted.
- A value for the *redshift*, z_i, is then extracted according to the probability given by the shell volume.
- For each couple of extracted values (L,z), fluxes are found through equation (3)
- spatial distribution of the objects is simulated by extracting the source position according to a probability distribution given by the clustering law: $w(\theta, z) = w_0(\frac{\theta}{\theta_0})^{\gamma} \cdot \epsilon(z)$

In Figure 1 we show an example of the modeled extragalactic sky.

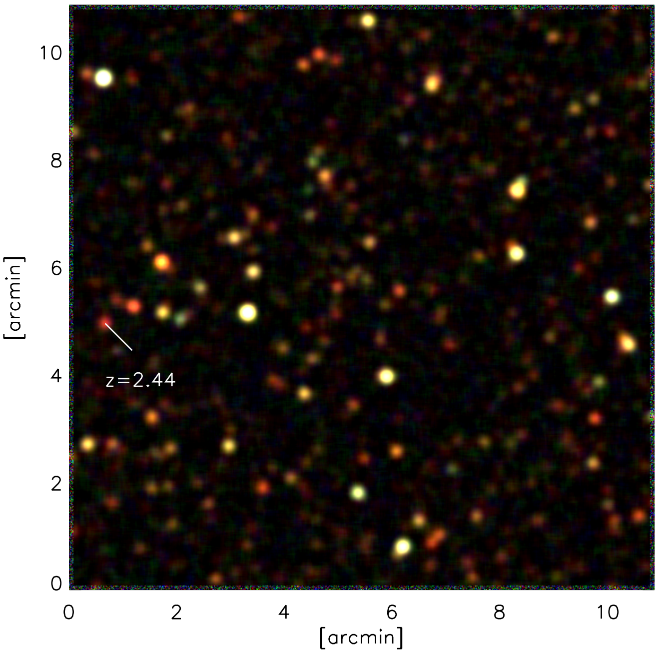

Figure 1. A simulation of the extragalactic sky in three different colours corresponding to the filters of the PACS instrument.

3.2. Simulation of the Galactic background

As second step we try to simulate the Galactic background. Reasons cited in § 2 show that a more sophisticated procedure must be considered here. A series of analytical and numerical algorithms (Vio, Andreani, Wamstecker 2001) have been developed to reproduce as closely as possible the characteristics of the Galactic cirrus emission.

The problem we have to tackle is the simulation of a generic random field characterized by a prescribed covariance function $\xi_R(\mathbf{r_1}, \mathbf{r_2})$, computed from the data of a given observed sky region.

The algorithms employed are able to reproduce a random field, $R(\mathbf{r})$, by mapping a zero-mean unit-variance Gaussian field $X(\mathbf{r})$ into $R(\mathbf{r})$ with the help of an appropriate function. Analytically this is possible only in very special cases, i.e. when the transforming function can be well approximated with a lognormal field ($L(\mathbf{r}) = \mathbf{e}^{\mu+\sigma \mathbf{X}(\mathbf{r})}$). In more general cases the appropriate function is chosen via numerical methods.

In Figure 2 an example of such a simulation is shown. Such a map is used as background to be added to the extragalactic sky simulated as described in 3.1.

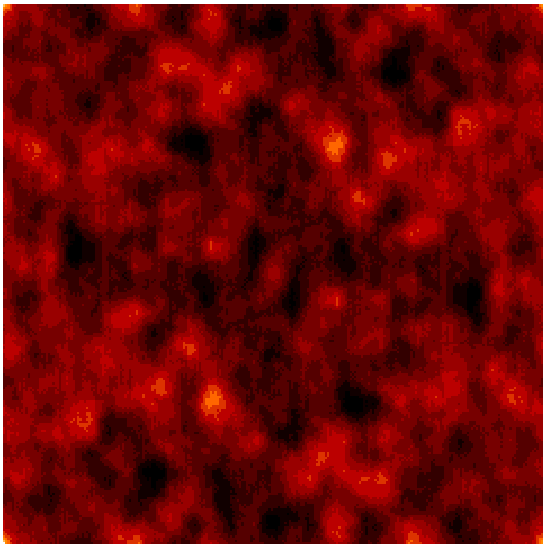

Figure 2. A simulation of a Galactic high-latitude region

4. The selection function

Finally the *mock* sky (Extragalactic + Galactic) must be ‘convolved’ with the *selection function* of a particular survey. It implies the extraction of source signal, according to predefined selection criteria (flux limits, extension, colours, ...).

Knowledge of this *function* is fundamental to assess the observational biases introduced by the observing procedures.

To this goal we need to define:

- *Photometric errors*, which have to be estimated from the knowledge of the instrument behaviour, i.e.:
  - the intrinsic noise of the detectors and of the read-out electronics,
  - flat-fielding errors including responsivity variation due to the environment (e.g. cosmic rays hitting the detector surface)
  - the ‘local’ backgrounds (zodiacal and cirrus emissions), estimated as in § 3.2.

- *flux limits and selection criteria* of the survey have to be applied to the resulting fluxes and colours of the mock sources.
- To reconstruct *sky maps* the effects on the source detection and resolution of the PSF of the instrument and the observing strategy must be then included.

5. Conclusions

A lot of work has still to be done to perform realistic simulations of the foreseen surveys with FIRST. In particular, depending on the scientific goal different observing strategies have to be devised and tested.

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