Starforming Galaxies Detected in Blind Spectroscopic Surveys with *SPICA*/SAFARI: Model Predictions

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ABSTRACT

By exploiting the galaxy evolutionary model of Cai et al. (2013), which reproduces the most recent estimates of the luminosity function of infrared-selected galaxies, Bonato et al. (2013) have predicted the number and redshift distribution of star forming galaxies detected in blind spectroscopic surveys with the SpicA FAR infrared Instrument (SAFARI) onboard of the *Space Infra-Red Telescope for Cosmology and Astrophysics* (*SPICA*). Here we summarize their results in relation to different survey strategies and for galaxies that are detected *in two or more lines*, a condition needed to ensure a robust redshift measurement. We conclude that in a reference survey of 450 hours the number of detections is maximized by keeping the integration time to 1 hour per field of view rather than going deeper over a smaller area. Only the statistics of $z > 3$ galaxies would benefit from a longer integration time per field of view, although their number would remain quite low (a few tens of objects for an investment of hundreds of hours). We envisage that follow-up observations of lensed galaxies discovered at sub-millimeter/millimeter wavelengths is a more efficient way to explore the mid- to far-infrared spectral properties of high redshift galaxies with *SPICA*/SAFARI.

1. INTRODUCTION

The star formation history in galaxies is one of the key processes we have to understand in order to reconstruct how the Universe evolved from small matter perturbations at the recombination epoch to the present richness of structures. While on large scales the evolution is driven by gravity, and numerical simulations in the framework of the current consensus cosmology have been remarkably successful in reproducing the galaxy distribution, on galaxy scales the complex baryon physics comes into play and current theories are still not up to the challenge of accurately modeling it. The only way to probe the physical processes at work in galaxies is by means of spectroscopy. While spectroscopic observations are routinely carried out at optical and near-IR wavelengths, the same observations are limited to small (and sometimes biased) samples of galaxies at longer wavelengths, where several key probes of the atomic, ionized and molecular phase of the interstellar medium are present (Spinoglio 1992). In the (sub-)millimeter the situation is rapidly improving thanks to the advent of instruments like the Atacama Large (sub-)Millimeter Array (ALMA), but at mid-/far-infrared wavelengths the spectral properties of galaxies remain almost un-explored, particularly in the distant Universe. In order to fill this gap, the Japan Aerospace Exploration Agency (JAXA) and its European collaborators are proposing the *Space Infra-Red Telescope for Cosmology and Astrophysics* (*SPICA*), that will host SAFARI (Roelfsema et al. 2012), an imaging spectrometer operating in the 34–210 μm wavelength range, with a $2' \times 2'$ field of view (FoV).

Recently Bonato et al. (2013) have worked out the number and redshift distribution of star forming galaxies detected in spectroscopic surveys with *SPICA*/SAFARI using the *hybrid* evolutionary model of Cai et al. (2013) for IR-galaxies and the latest values of the SAFARI line sensitivities. Here we summarize their results by focusing on galaxies detected in *at least two lines*, a condition necessary to ensure a robust redshift determination.

2. MODEL LUMINOSITY FUNCTION

The model by Cai et al. (2013) combines a physical forward approach for the evolution of high-redshift proto-spheroidal galaxies (Lapi et al. 2011), with a phenomenological backward approach for late-type galaxies and AGNs. The model builds on the observational evidence that relatively old (age $\gtrsim$8–9 Gyr) stellar populations are found in early-type galaxies and in massive bulges of Sa galaxies while irregular galaxies and the disc component of spirals contain younger stellar populations (age $\lesssim$7 Gyr). Therefore, early-type (proto-spheroidal) galaxies are the dominant star-forming population at $z \geq 1.5$, while IR galaxies at $z < 1.5$ are mostly late-type "cold" (normal) and "warm" (starburst) galaxies. The former are modelled within the standard bottom-up scenario of dark matter structure formation, following the cooling of baryons within dark matter haloes and accounting for the effect of feedback from supernovae explosions and from the activity associated with a growing super-massive black hole in the central region of the galaxy (Granato et al. 2004; Lapi et al. 2006, 2011). The evolution of late-type (warm starburst and cold normal) galaxies and of $z < 1.5$ type-1 and type-2 AGNs is described using a parametric phenomenological evolution approach, based on a power-law density

Table 1. Number of late-type galaxies and of proto-spheroids *detected in two or more lines* (i.e. the line considered plus at least another one) by a *SPICA*/SAFARI survey covering 0.5 deg^2 in 1 hr integration per FoV (2^{nd} and 3^{rd} columns), in 4 hr integration per FoV (4^{th} and 5^{th} columns) and in 9 hr integration per FoV (6^{th} and 7^{th} columns). The total number of objects detected in at least two lines (regardless of which lines are actually detected) is shown in the last line, while the value in parentheses represents the subsample of proto-spheroids with redshift $z > 3$.

Spectral line	1 hour per FoV		4 hours per FoV		9 hours per FoV	
μm	late-type	proto-sph.	late-type	proto-sph.	late-type	proto-sph.
PAH 11.25	1	508	15	1207	39	1922
[Ne II] 12.81	12	242	60	612	148	1000
[Ne III] 15.55	25	60	102	176	214	314
(H_2) 17.03	11	11	45	48	102	95
[S III] 18.71	220	125	647	340	1101	583
[S III] 33.48	1591	334	3571	885	5253	1462
[Si II] 34.82	2187	479	4615	1198	6623	1969
[O III] 51.81	2638	610	5238	1395	7370	2186
[N III] 57.32	728	139	2086	383	3437	650
[O I] 63.18	2010	307	4403	714	6363	1117
[O III] 88.36	2545	27	4755	108	6404	238
[N II] 121.9	410	0	860	0	1252	0
[O I] 145.5	137	0	281	0	412	0
[C II] 157.7	625	0	1032	0	1361	0
≥2 lines	3649	899 (66)	6932	2094 (225)	9489	3332 (434)

and luminosity evolution. The model reproduces a wide range of multiwavelength data (see Cai et al. 2013), including the recent determination of the IR luminosity function of star forming galaxies (Gruppioni et al. 2013); in particular it accounts for the transition from Euclidean to extremely steep counts at (sub-)mm wavelengths (Clements et al. 2010) and for the (sub-)mm counts of strongly lensed galaxies (Negrello et al. 2010; Viera et al. 2010).

In working out their predictions, Bonato et al. (2013) have focused on star forming galaxies (i.e. late-type galaxies and proto-spheroids) alone, as they provide the dominant contribution to the IR luminosity function (the contribution of AGNs to the line luminosity function will be discussed in a forthcoming paper). The IR continuum (8–1000 μm) luminosity is converted into a line luminosity assuming a constant line-to-IR luminosity ratio that is calibrated on data available in the literature and is also tested against simulations based on the public library of line luminosities compiled by Panuzzo et al. (2003). Predictions for the number and redshift distribution of galaxies detected in two or more lines are worked out using Monte Carlo simulations in which infrared galaxies are drawn from the model IR luminosity function and the line luminosities are randomly assigned to each source by accounting for the effect of dispersion in the line-to-IR luminosity ratios. The final number of detections is obtained by averaging over the results of 300 simulated catalogues.

3. SPECTROSCOPIC SURVEYS WITH *SPICA*/SAFARI: PREDICTIONS

The expected SAFARI 5σ line detection limits for an integration of 1 hour per field of view (FoV) are 3.7×10^{-19} W/m^2 for the first band (34–60 μm), 3.4×10^{-19} W/m^2 for the second band (60–110 μm) and 2.9×10^{-19} W/m^2 for the third band (110–210 μm) (B. Sibthorpe, private communication).

Following Spinoglio et al. (2012), Bonato et al. (2013) consider a reference spectroscopic survey of **450 hours** and **1 hour of integration time per FoV** ($t_{\rm FoV}$). This corresponds to a total areal coverage of 0.5 deg^2 (excluding overheads). The number of galaxies detected in two or more lines by such a survey is reported at the bottom of Table 1 for late-type galaxies (second column) and proto-spheroids (third column; with the number of $z > 3$ detections indicated in parentheses). Also shown in the table is the number of detections in each spectral line for objects detected in at least two lines (i.e. each of the thousands of galaxies seen in e.g. [O III] 51.81 μm is also detected in one or more of the lines listed in the same table). The brightest lines, which provide the highest number of detections, are [S III] 33.48 μm, [Si II] 34.82 μm, [O III] 51.81 μm, [O I] 63.18 μm, [O III] 88.36 μm and [N II] 121.9 μm. These lines will represent the most useful redshift indicators and the most easily available probes of the physical conditions in star forming galaxies detected by SAFARI. The redshift distribution of galaxies detected in at least two lines in the reference spectroscopic survey is shown by the blue histogram in Figure 1. The majority of galaxies have $z \lesssim 2$ with only ~ 70 detections above $z = 3$. The way to

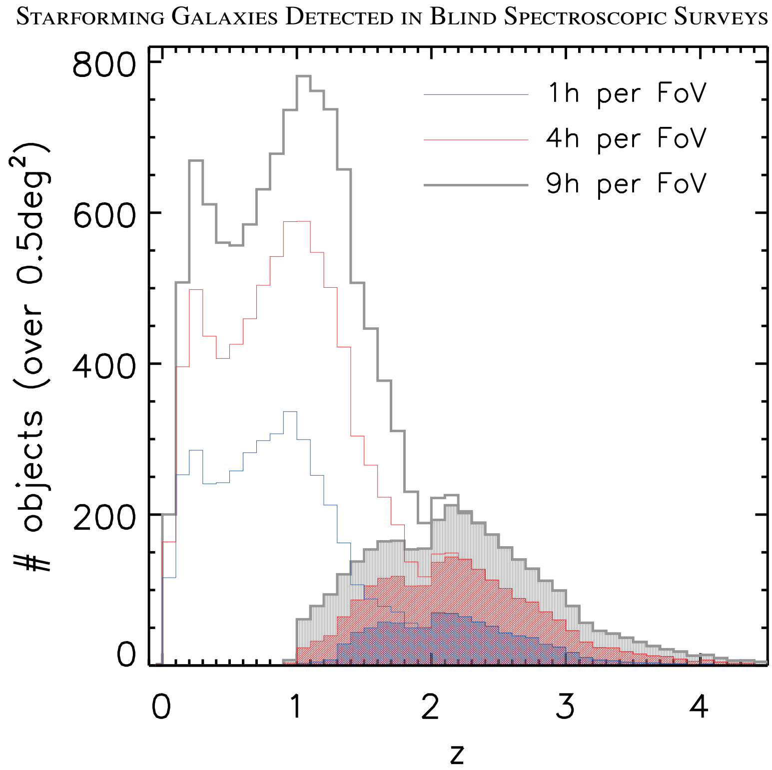

Figure 1. Number of star forming galaxies *detected in 2 or more lines* in a spectroscopic survey of 0.5 deg^2 with *SPICA*/SAFARI for 1 hr integration per FoV (*blue line*), 4 hr integration per FoV (*red line*) and 9 hr integration per FoV (*grey line*). The shaded histograms show the contribution of proto-spheroids.

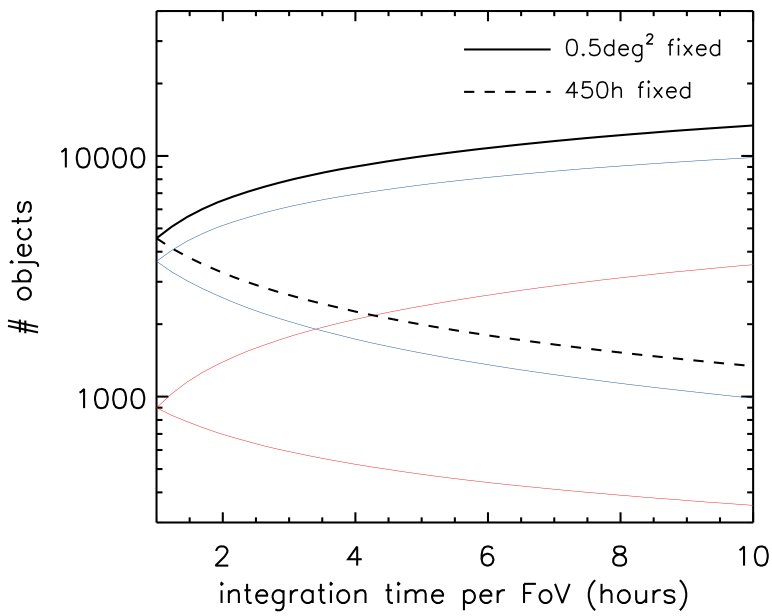

Figure 2. Number of star forming galaxies (*black curves*) *detected in 2 or more lines* as a function of the integration time per FoV for a *SPICA*/SAFARI spectroscopic survey of 0.5 deg^2 (solid curves) and of 450 hours (dashed curves). The contributions of late-type galaxies and of proto-spheroids are shown in blue and in red, respectively.

increase the statistics of high redshift galaxies is to improve the line sensitivity by means of longer integration time per FoV. The effect is illustrated by the black dashed line in Figure 2, where the number of galaxies detected in two or more lines is shown as a function of $t_{\rm FoV}$. As the integration time per FoV increases, the line sensitivity decreases by a factor $\sqrt{t_{\rm FoV}}$ while the area is scaled down by a factor $1/t_{\rm FoV}$. The net effect is the loss of statistics as the decreasing number of detections due to the smaller areal coverage is not overcame by the increasing number density of galaxies. In fact, around the faintest line fluxes probed by SAFARI, the line integral number counts have slope $\gamma \sim 1$ (with $N(> F_\ell) \propto F_\ell^{-\gamma}$, where F_ℓ is the line flux).

Alternatively, one can keep the area to 0.5 deg^2 and just increase the amount of time invested in the survey. The result of this approach is shown by the solid lines in Figure 2, and also reported in Table 1 for an $t_{\rm FoV} = 4$ hours and $t_{\rm FoV} = 9$ hours per FoV. The corresponding redshift distributions are shown in Figure 1. We find that improving the line sensitivity by a factor of 3 (i.e. $t_{\rm FoV} = 9$ hours) will gain about ×6 more galaxies detected in at least two lines at $z > 3$ compared to what expected for the reference survey. However this would require an investment of 4050 hours for the entire survey. A wiser approach to the study of star formation activity in the distant Universe would be to follow-up the hundreds of high redshift lensed galaxies discovered meanwhile at sub-millimeter and millimeter wavelengths (Negrello et al. 2010; Bussmann et al. 2013; Vieira et al. 2013). With an *apparent* infrared luminosity exceeding $10^{13}\,L_\odot$, those galaxies will be detected at 5σ in several mid-/far-IR lines in about 15 minutes, or less, with *SPICA*/SAFARI.

4. CONCLUSIONS

In light of the predictions made by Bonato et al. (2013) for galaxies detectable in at least two lines with *SPICA*/SAFARI, we conclude that a spectroscopic survey of 450 hours would maximize the number of detections if the integration time is kept to 1 hour per FoV, for a total observed area of 0.5 deg^2, rather than going deeper over smaller areas. On the other hand, to compensate for the relatively small statistics of $z > 3$ detections we suggest to integrate the spectroscopic survey with a follow-up program focusing on high redshift lensed galaxies discovered meanwhile at sub-mm/millimeter wavelengths.

Mattia Negrello wishes to thank prof. Hideo Matsuhara for financially supporting his attendance to the conference. We also acknowledge financial support from ASI/INAF Agreement I/072/09/0 for the Planck LFI activity of Phase E2 and from PRIN INAF 2012 project *'Looking into the dust-obscured phase of galaxy formation through cosmic zoom lenses in the Herschel Astrophysical Terahertz Large Area Survey'*.

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