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EXPLORING THE SPECTROSCOPIC CAPABILITIES OF SAFARI FOR STUDIES OF THE DISTANT UNIVERSE

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Abstract

Deep photometric surveys in the submm and FIR have identified a previously unknown population of distant, dusty galaxies that emit the bulk of their significant bolometric luminosity in the rest-frame IR. Determining the nature of these sources along with what powers their prodigious submm/FIR output is key to securing the place of this cosmologically significant population on the evolutionary pathway of galaxies. Deep MIR and FIR spectroscopy presents the best prospects for interrogating this distant and highly obscured population. In this paper we present the preliminary results of a quantitative study to determine how efficient SAFARI will be at making deep spectroscopic surveys in the MIR and FIR, and introduce a new SAFARI-specific diagnostic from the rest-frame MIR that can be used to differentiate between AGN and starbursts using lines that fall in the SAFARI waveband in objects at $z > 0.4$.

Key words: Galaxies: high-redshift, FIR/MIR spectroscopy, surveys – Missions: SPICA

1. Introduction

Deep cosmological surveys at submillimetre (submm) and mid- and far-infrared (MIR/FIR) wavelengths continue to resolve the Cosmic IR Background (CIRB) into dusty, distant galaxies which emit a significant fraction of their bolometric luminosity in the restframe MIR/FIR/submm. These luminous and ultraluminous IR galaxies ((U)LIRGs) are relatively rare in the local Universe, and account for less than 5% of the infrared emission produced by galaxies. This population evolves strongly however, and at $z \sim 1$ and beyond the space density of (U)LIRGs increases by factors of 100-1000, and contributes very significantly to the CIRB.

By current estimates, tens of % of the CIRB can be resolved into distant, IR-bright galaxies at FIR and submm wavelengths, with even higher percentages in the MIR. The overall task of determining the redshifts of these galaxies, establishing what physical processes drive their prodigious IR output and how exactly they fit into and contrain galaxy evolution models is one of the most topical and significant challenges in current observational cosmology. Many diagnostic tools across the electromagnetic spectrum have been employed to-date to interrogate the distant IR-bright population. The same dust that is responsible for the huge IR input absorbs much of the light shortward of the MIR, making the detection of the standard optical/IR/UV spectral line diagnostics used in local studies of active galactic nuclei (AGN) and starburst galaxies (SB) extremely challenging with even the largest optical telescopes. To-date, the total number of FIR and submm sources known has been relatively small, and it has been possible to invest the significant periods of observing time required to characterise individual objects in the optical, IR and also with the IRS on Spitzer (Chapman et al., 2005; Marleau et al., 2007; Menendez et al., 2009). The broad conclusion from such studies is, as with the local (U)LIRG population, that the astrophysical engines powering these sources and driving their evolution are fueled by mass accretion (onto massive central black holes), and huge bursts of star formation. There is increasing evidence from both Spitzer (Menendez et al., 2009) and ground-based studies (Hailey-Dunsheath, 2008) of the rest-frame FIR emission lines to suggest, however, that the emission from distant (U)LIRGS can differ significantly from that of local ULIRGs, resembling that seen in lower luminosity starbursts.

The large Herschel surveys (Hermes, PEP and GOODS-Herschel) along with the deep SAFARI surveys will reveal many hundreds of thousands of submm/FIR sources. With such large numbers, new strategies for determining both the nature and cosmic distribution of this distant IR-bright galaxy population are required.

In this paper we present the preliminary results of a small study to determine the efficiency and efficacy of SAFARI in undertaking deep spectroscopic surveys in the rest-frame MIR and FIR. We introduce a new SAFARI-specific rest-frame MIR diagnostic that can be used to differentiate between AGN and SB. We summarise the redshifts out to which SAFARI will be able to detect a selection of FIR and MIR lines, and present the results of calculations to evaluate the number of sources that we might expect to see, in different key rest-frame MIR emission lines, per SAFARI field of view.

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2. The MIR/FIR tool box - AGN/starburst diagnostics

The rest-frame MIR and FIR waveband ($5-210\mu$m) plays host to an extensive range of spectral lines, with critical densities and ionization potentials that cover a very broad range of physical conditions, stretching from those found in relatively low-excitation regions such as photon-dominated regions and HII-regions, to the more extreme conditions of the increasingly ionised regions surrounding a central AGN (Spinoglio, 2007). The diagnostic power of these lines is considerable: with combinations of two or more lines one can not only determine source redshift but, very much more importantly, by taking ratios of lines with very different excitation parameters one can determine the physical processes - starformation or AGN growth - driving the evolution of the source. The power of combinations of MIR lines and PAH feature ratios for tracing AGN/starburst activity has been demonstrated in the local Universe by ISO (Genzel et al., 1998) (eg. [OIV]25.9μm / [NeII]12.8μm vs. relative strength of the 7.7μm PAH feature) and Spitzer (eg. [OIV]25.9μm / [NeII]12.8μm vs. [NeV]14.3μm / [NeII]12.8μm (Veilleux et al., 2009).

The ideal SAFARI AGN vs. starburst diagnostic would cover as wide a redshift interval as possible, and would rely solely on SAFARI data. The [NeII]12.3μm line in the commonly used ratio of [NeV]14.3 μm /[NeII]12.3 μm does not move into the SAFARI waveband until $z > 1.7$, and the 7.7 μm PAH feature is only seen in sources with $z > 3.4$, and so neither can be used over a broad redshift range using SAFARI-only data. By substituting the [NeII] line with the longer wavelength [SIII]34μm line that traces very similar excitation conditions, we have a rest-frame MIR line ratio diagnostic that uses SAFARI data exclusively, and that covers all redshifts beyond z>0.4 (Figure 1). How effective such a diagnostic turns out to be depends not only on how well it can separate AGN from SB, but very practically on how efficient SAFARI will be at detecting the distant line emission. It is clear from previous work (see Figure 5 of Swinyard & Nakagawa (2009)) that with its goal sensitivity SAFARI will be capable of detecting emission from many of the key MIR and FIR lines from objects with $L_{IR} > 10^{11} L_{\odot}$ out to redshifts of $z > 1$. With its wide-band imaging capability, SAFARI will be able to observe the full $34-210\mu m$ waveband over more than one source per observation, and thus the efficiency of SAFARI is a function of its sensitivity and of the intrinsic number of distant IR-bright galaxies per field of view (FoV).

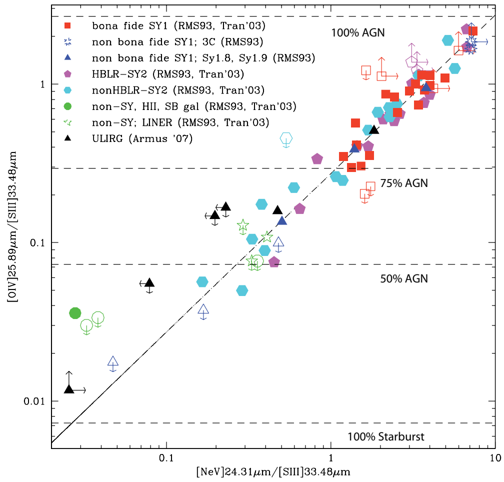

Figure 1. A plot to illustrate the discriminatory power of a new, SAFARI specific line ratio diagnostic to differentiate between AGN and starburst. We have substituted the traditionally-used [NeII] line with the [SIII]34.5μm line which traces very similar conditions, to realise a diagnostic that requires only lines that will be observed in a single observation with SAFARI, and that will be available for sources at $z > 0.4$. Pure AGN and starburts line at the extreme ends of the plot. Data in this plot is taken from Tommasin et al., 2009 (to be submitted) and Armus et al., 2007.

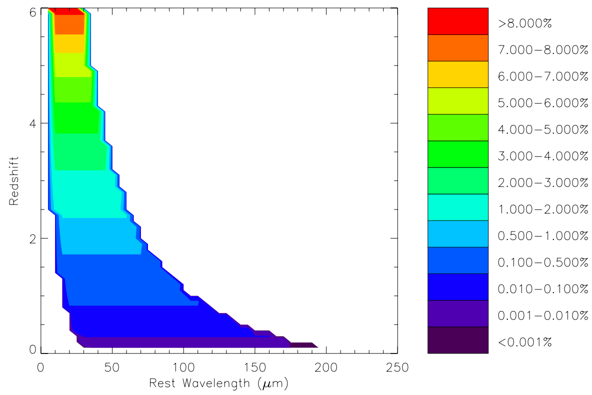

Figure 2. A plot of the minimum % of the total IR luminosity of a source with $L_{IR} = 10^{11} L_{sol}$ that an emission line at a given rest wavelength, needs to contain in order to be detected by SAFARI, at redshift, z

3. Deep MIR/FIR line surveys with SAFARI

3.1. Modelling the LIR-bright galaxy population

We used a two-step method to determine the number of high-redshift sources that might be expected to be detected per individual SAFARI FoV. First we determine an estimate of the IR luminosity/redshift distribution of the extragalactic population, n(L_{IR}, z) per square degree[1]; we then take locally-measured line-to-IR luminosity ratios (for a range of different types of sources) to calculate the fractional IR luminosity that is carried in a given emission line. With a knowledge of the redshift and IR luminosity of a particular source we can calculate the expected source

[1] Here, we use the wavelength range of 8–100μm to define L_{IR}

Fine structure line (wavelength)	Typical % of L_{IR} in the line	Redshift z_{max} of line at 210 μm	Redshift to which line with % in col 2 can be seen for $L_{IR} = 10^{10} L_\odot$	$L_{IR} = 10^{11} L_\odot$	% of L_{IR} $= 10^{10} L_{sol}$ to detect line at z_{max}	% of L_{IR} $= 10^{11} L_{sol}$ to detect line at z_{max}
$[OIII]52\mu m$	0.05	3.04	0.21	0.61	17.8	1.8
$[NIII]57\mu m$	0.035	2.68	0.17	0.52	13.5	1.4
$[OI]63\mu m$	0.125	2.33	0.32	0.92	9.9	1.0
$[OIII]88\mu m$	0.05	1.39	0.21	0.61	3.1	0.3
$[NII]122\mu m$	0.02	0.72	0.13	0.39	0.73	0.07
$[OI]145\mu m$	0.0075	0.45	0.08	0.25	0.26	0.03
$[CII]157\mu m$	0.125	0.33	0.32	(0.92)	0.13	0.01

Table 1. The detectability of the 7 principal FIR diagnostic lines with SAFARI in a 1hr integration.

line to confirm that line falls into the SAFARI band and that SAFARI has the sensitivity to detect the source line emission.

In the first step we used a fake catalogue generated by Le Borgne, Elbaz and collaborators (LeBorgne et al., 2009) to determine n(L_{IR},z) per square degree on the sky. The catalogue itself is generated using an empirically-based total infrared luminosity function which provides the best global fit to the observed galaxy counts at 15, 24, 70, 160, and 850 μm. As a primary selection, all sources with $z < 5$ and $10 < log_{10}L_{IR} < 14$ are included in the catalogue, and the sample is complete for a flux of $S_{24} > 0.005$ mJy. The total area of the catalogue is 10 square degrees.

We then used ratios of line-to-total-FIR-luminosity for AGN-dominated (LIRG/ULIRG) and starburst-dominated (LIRG/ULIRG) galaxies determined (a) in the case of the MIR lines, from the Spitzer GOALS legacy programme (Veilleux et al., 2009) along with ISO studies of AGN and starburst (Sturm et al., 2002; Verma et al., 2003);(b) for the FIR from predictions based in ISO observations (Brauher et al., 2008).We took the strongest of the FIR and MIR lines as test cases. To make our calculations we have assumed a wavelength-independent, goal sensitivity for SAFARI of $5\sigma - 1\text{hr} = 2 \times 10^{-19}\text{Wm}^{-2}$, an EdS cosmology with $H_o = 72\text{kms}^{-1}\text{Mpc}^{-1}$, and have considered the cases for which the line ratios are (a) independent of redshift (no-evolution) and (b) evolve *relative* to the continuum with $(1+z)^2$. An additional assumption that we make is that $L_{FIR} \sim L_{IR}$ which, to zero order, is correct[2].

4. Results

The detectability of high-z sources using SAFARI is summarised in Tables 2 (FIR lines) and 4 (MIR lines) , and presented graphically, in summary, in Figure 2.

[2] Where L_{FIR} is taken as being proportional to $2.58 \times S_{60\mu m} + S_{100\mu m}$, where $S_{60\mu m}$ and $S_{100\mu m}$ are the IRAS fluxes

4.1. FIR predictions:

Sensitivity-wise, the brightest of the FIR lines, [OI]63μm and [CII]157μm, can be seen out to redshifts of $z \sim 0.92$ and $z \sim 0.32$ in a source with $L_{IR} = 10^{11}L_\odot$ and $L_{IR} = 10^{10}L_\odot$ respectively. The [CII] line shifts out of the SAFARI band at $z \sim 0.33$, re-emerging in the ALMA bands at $z > 2$. This is the only one of the strong FIR lines which shifts out of the SAFARI waveband before becoming too weak to detect above the instrumental noise in a 1hr integration. Work by Spinoglio&Malkan (Spinoglio & Malkan, 2005) suggests that the FIR lines and line ratio combinations can be used as a diagnostic of AGN/starburst activity, however this remains to be calibrated properly by Herschel.

4.2. MIR predictions:

We have considered the detectability of the [NeV]24.3μm, [OIV]25.9μm, [SIII]33.5μm and [SiII]34.8μm lines in the redshift ranges $0.4 < z < 1$, $1 < z < 2$ and $2 < z < 3$ to span the redshift range of the peak of the starformation rate density/black hole accretion rate (Merloni et al., 2006). The minimum redshift is that required to redshift the [OIV] line into the SAFARI waveband. Our results suggest that we will detect $10 - 30$ sources per FoV, depending on which line we choose, with higher numbers predicted if weno allow the line-to-IR-luminosity ratio to evolve with redshift (see numbers in Table 4 in rows marked (e)). In making the calculations we have assumed that all sources of a given (L_{IR}, z) are either SB or AGN. This is clearly an oversimplification and so the true number of sources that we might expect to see will be somewhere between the numbers tabulated for the two types of source. We note that when considering the no-evolution case, we have the sensitivity to detect line emission from only a fraction of the total number of sources that are predicted by the flux-limited models of Le Borgne et al. to be in a single SAFARI FoV (see column 8 in Table 4).

Redshift range		[NeV] 24.3μm SB	AGN	[OIV] 25.9μm SB	AGN	[SIII] 33.5μm SB/AGN	[SiII] 34.8μm SB/AGN	Total no: of FIR sources/FoV
$0.4 < z < 1$	n	-	0.	-	1.1	13.0	14.1	29.3
	e		9.3		9.3	20.4	22.9	
$1 < z < 2$	n	-	7.3	-	18.7	7.3	9	56.2
	e	-	26.3	-	42.3	26.3	29.4	
$2 < z < 3$	n	-	1.2	-	7.9	1.2	1.7	27.1
	e	-	17.3		26.5	17.3	19.5	
$z > 3$	n	-	0.	-	1.1	0.	0.1	9.3
	e		9.3		9.3	9.3	9.3	

Table 2. A table summarising the predicted number of sources that will be detected per SAFARI FoV, over a range of redshift intervals in a selection of key MIR emission lines. We have assumed that all IR-bright sources in a given FoV are either pure AGN or pure SB, and thus the true numbers that will be detected will be somewhere between the figures for the two types of source.

Our calculations suggest that we will have sufficient sensitivity with SAFARI to use the diagnostic ratio described in subsection 2 in the redshift range $0.4 < z < 4$ to characterise several sources in a single SAFARI pointing. We have assumed a random distribution of sources across the sky: significant clustering of IR-bright sources has been observed with Spitzer (eg. Farrah et al. (2006)), and thus when targeting such regions we anticipate there being as much as a factor of 10 more IR-bright sources per FoV.

5. Conclusions and future work

We have made simple calculations to estimate the number of distant IR-bright galaxies that we will be able to detect per SAFARI FoV in a single hour's integration. Using the (L_{IR},z) source densities determined by models of LeBorgne, Elbaz and collaborators we expect to detect between 5 and 20 sources over the redshift range $0.4 < z < 3$ per FoV per 1 hour integration assuming goal sensitivity in a number of the key MIR diagnostic lines if we assume a 50:50 distribution between AGN and SB, and are conducting blind surveys. The number of sources per FoV could increase significantly if we were to target regions where IR-bright galaxies are known to be clustered, or if an evolution of the fractional line -to-IR luminosity were to be observed. SAFARI will be able to detect the FIR line emission lines from galaxies with $L_{IR} \sim 10^{11} L_\odot$ out to $0.25 < z < 0.9$, depending on the choice of line. We have introduced a new diagnostic to differentiate AGN from SB using rest-frame MIR lines that redshift into the SAFARI band at redshifts of $z > 0.4$; we expect to be able to use this to characterize several sources per SAFARI FoV.

In future work we will use other galaxy evolution models to predict the number of sources of a given L_{IR}, z that one might expect to find in a SAFARI FoV, along with the models of Gruppioni et al. described elsewhere in this proceeding to account explicitly for the estimated numbers of AGN and starbursts. We will also extend our choice of lines to include molecular hydrogen and PAHs, and investigate further combinations of MIR/FIR lines as identifiers of distant AGN and starbursts.

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