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Galaxy Populations from Deep ISO Surveys

By

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Abstract: I discuss some of the main extra-galactic field surveys which have been undertaken by the Infrared Space Observatory (ISO). I review the findings from the source counts analyses and then examine some of the more recent detailed investigations into the explicit nature of the populations that make up these source counts.

1. ISO SURVEYS

Depending on how you count them, ISO (Kessler et al. 1996) undertook around fifteen independent field surveys to explore the extra-galactic populations. These surveys primarily used the ISO-PHOT (Lemke et al. 1996) and ISO-CAM (Cesarsky et al. 1996) instruments. As shown in Table 1 and illustrated in Figure 1 these surveys explored the full extent of ISO's parameter space in terms of wavelength, area and depth.

This is an attempt to collect together some of the findings of these surveys. I will group the surveys by wavelength, since the populations explored at different wavelengths are expected to be somewhat different.

1.1 Mid-IR Surveys 6.7–15μm

Surveys in this wavelength regime tend to pick up emission from hotter sources such as AGN or luminous starbursts, they also pick up "cirrus" emission from normal galaxies. While these bands are located far from the peak of the typical starbursts spectral energy distribution it has been noted that the PAH features which do fall in these bands can be used as a good measure of star-formation activity. Surveys in these bands are the HDF surveys in the North and South; CFRS; ELAIS; the ISOCAM guaranteed time Extra Galactic Surveys, the Comet fields, the Japanese Lockman and Selected Area surveys and the CAM parallel mode survey.

1.2 Far-IR Surveys 50–100μm

These wavelengths are located at the peak of the rest-frame emission from obscured star formation and thus provide the most direct estimate of the obscured bolometric output in star-

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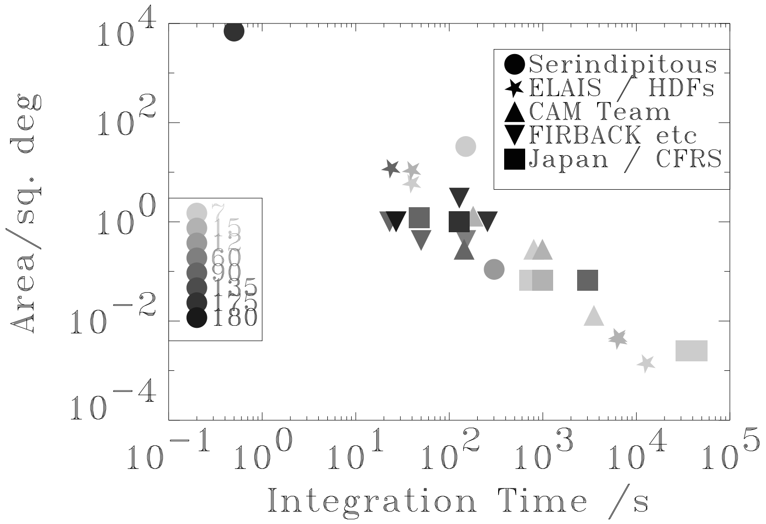

Fig. 1: Comparison of *ISO* surveys: area vs. depth. All the surveys in Table 1 are plotted. (Adapted from Oliver et al. 2000)

forming galaxies. Surveys in this band are that of SA57, the Japanese surveys, ELAIS, CIBR, and CFRS.

1.3 "Cool" FIR Surveys 120–200μm

I use this term to denote bands beyond the normal peak in a star-burst emission. Surveys at these bands tend to pick up galaxies which are "cool" either because the energy distributions have been "cooled" simply by virtue of their high redshift, or because they are intrinsically cool but local. Surveys in this band are FIRBack, ELAIS, Japanese surveys, the PHOT slew surveys, and CIBR.

2. COUNTS

2.1 Mid-Infrared Counts

The ELAIS 15μm counts Serjeant et al. (2000), illustrated in Figure 2, were shown to agree with many strongly evolving models such as those of Franceschini et al. (1994), Pearson & Rowan-Robinson (1996), Xu et al. (1998) which had been based on IRAS counts, while being inconsistent with at least one non-evolving model that of Xu et al. (1998). Deeper counts such as those of the ISO–HDF Oliver et al. (1997) amplify this picture of strongly evolving populations and the summary presented by Elbaz et al. (1999) (also shown in Figure 2) suggests that the deepest cluster–lens surveys have seen a turn over in the counts and thus the beginning of the end of these evolving populations.

Table 1: Field Surveys with ISO, ordered roughly in decreasing area. References: 1 – Bogun et al. (1996), 2 – Siebenmorgen et al. (1996), 3 – Oliver, et al. (2000b), 4 – Elbaz et al. (1999), 5 – Dole et al. (1999), 6 – Juvela et al. (2000), 7 – Linden-Vørnle (2000), 8 – Elbaz et al. (1999) 9 – Clements et al. (1996), 10 – Flores et al. (1999a, b), 11 – Elbaz et al. (1999), 12 – Oliver et al. (in preparation), 13 – Taniguchi et al. (1997), 14 – Kawara et al. (1998), 15 – Serjeant et al. (1997)

Survey Name	[e.g. ref]	Wavelength /μm	Integration /s	Area /sqdeg
PHT Serendipity Survey	1	175	0.5	7000
CAM Parallel Mode	2	6.7	150	33
ELAIS	3	6.7,15,90,175	40, 40, 24, 128	6, 11, 12,1
CAM Shallow	4	15	180	1.3
FIRBACK	5	175	256, 128	1, 3
CIBR	6	90, 135,180	23, 27, 27	1, 1, 1
SA 57	7	60, 90	150, 50	0.42,0.42
CAM Deep	8	6.7, 15, 90	800, 990, 144	0.28, 0.28, 0.28
Comet fields	9	12	302	0.11
CFRS	10	6.7,15,60,90	720, 1000, 3000,3000	0.067.0.067.0.067,0.067
CAM Ultra-Deep	11	6.7	3520	0.013
ISOHDF South	12	6.7, 15	> 6400, > 6400	4.7×10^{-3}, 4.7×10^{-3}
Deep Lockman	13,14	6.7, 90, 175	44640, 48, 128	2.5×10^{-3}, 1.2 , 1
ISOHDF North	15	6.7, 15	12800, 6400	1.4×10^{-3}, 4.2×10^{-3}

2.2 FIR Counts

The FIR source counts also show good evidence for evolution. E.g. the ELAIS 90μm counts of Efstathiou et al. (2000) confirm the strong evolution expected from extrapolation from IRAS studies, see Figure 3. FIR counts from other ISO surveys are given in Juvela et al. (2000) and Linden-Vørnle (2000).

2.3 "cool" FIR Counts

The 175μm counts have attracted a lot of attention since they are more difficult to explain (e.g. Dole et al. 1999 and references therein). The counts exceed models extrapolated from IRAS. To illustrate this Figure 4 shows the Dole et al. (2000) attempt to explain the "cool" counts. This model allowed a strong evolution in the ultra luminous IRAS galaxies and was constrained by both the 175μm counts and the FIR background. It should be stressed that such an extreme model is not a unique fit to the data, but illustrates the lengths to which one needs to go to explain these data.

3. BEYOND COUNTS

The counts are challenging, they show strong evolution, and may suggest new populations. However, in isolation they do not tell us what the nature of the sources is. The current effort is now strongly focused on more detailed investigations of these populations. I pick three particular results for discussion.

The first is from the ELAIS survey and is simply a summary of spectral classifications from

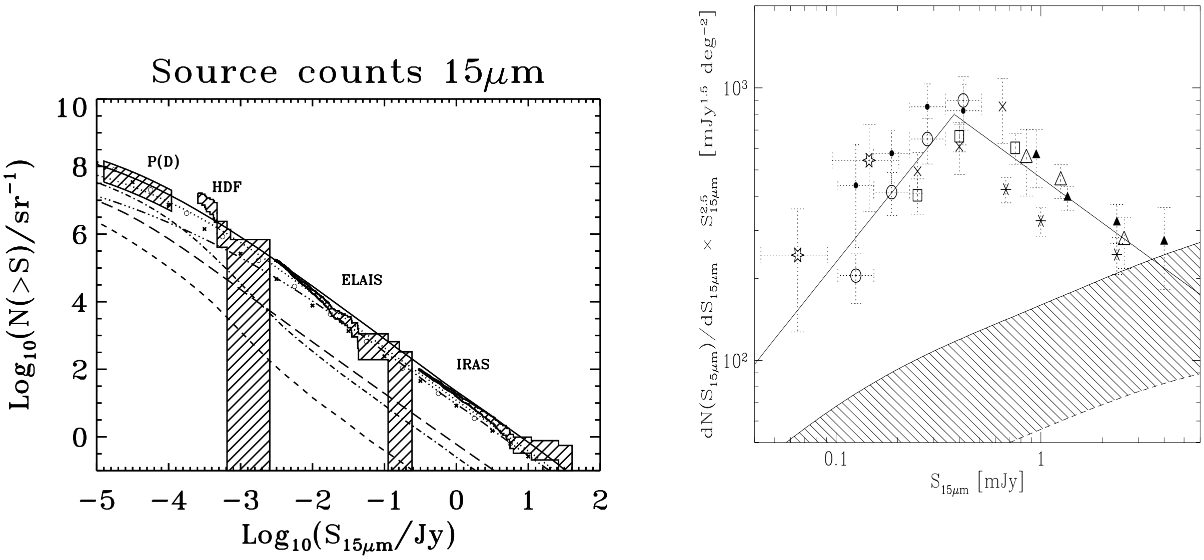

Fig. 2: Number counts of 15μm galaxies. Left: integral counts. Shaded regions show the ranges spanned by $\pm 1\sigma$ uncertainties. Also shown are the source counts and P(D) analysis from the Hubble Deep Field (Oliver et al. 1997; Aussel et al. 1999). The IRAS counts are estimated from the 12μm counts. The Franceschini et al. (1994) source count model is over-plotted. The model spiral contribution is shown as a dotted line, ellipticals as a dashed line, S0 as a dash-dot line, star-bursts as a dash-dot-dot-dot line and AGN as a long dashed line. The total population model is shown as a full line. Also plotted are the Guiderdoni et al. (1998) models A and E, as small filled crosses and small open circles respectively. Figure taken from Serjeant et al. (2000) Right: differential, Euclidean normalized counts. Data points: A2390 (open stars), ISO–HDF North (open circles), ISO–HDF-South (filled circles), Marano FIRBack (MFB) Ultra-Deep (open squares), Marano Ultra-Deep (crosses), MFB Deep (stars), Lockman Deep (open triangles), Lockman Shallow (filled triangles). The hatched area shows the range of expectations assuming no evolution. Figure taken from Elbaz et al. (1999)

the campaigns using 2dF and the ESO telescopes, Gruppioni et al. (in preparation) and La Franca et al. (in preparation), presented by Oliver et al. (2000a) and shown in Table 2. The completeness and homogeneity of this list is not taken into account and so this table only gives a very crude picture. With that caveat in mind we do see that one third of these, relatively bright, mainly 15μm sources have AGN of one sort or another. A second important result arises from the VLT spectroscopy of 15μm ISO-HDF-South sources undertaken by Rigopoulou et al. (2000) and illustrated in Figure 5. This indicates that many of the fainter 15μm sources, making up the peak in the differential counts are star-forming galaxies, hinting that the population mix may be changing as we move to fainter fluxes.

The third result comes from studies of the 175μm sources. These have been particularly hard to identify spectroscopically but the sub-mm photometric study of Scott et al. (2000) is instructive. Figure 6 shows the average fluxes of 10 sources compared with some simply SEDs. From this it appears that the best fitting models would have the sources at relatively modest redshifts.

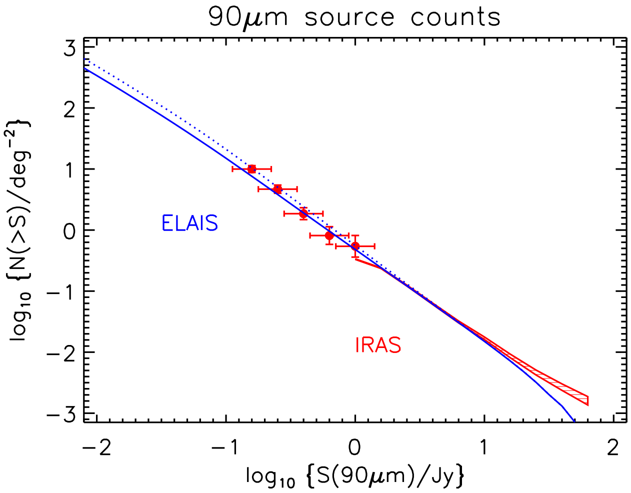

Fig. 3: ELAIS and IRAS 90μm source counts. The solid line and dotted lines are the counts predicted by the models A and E (respectively) of Guiderdoni et al. (1998). Taken from Efstathiou et al. (2000).

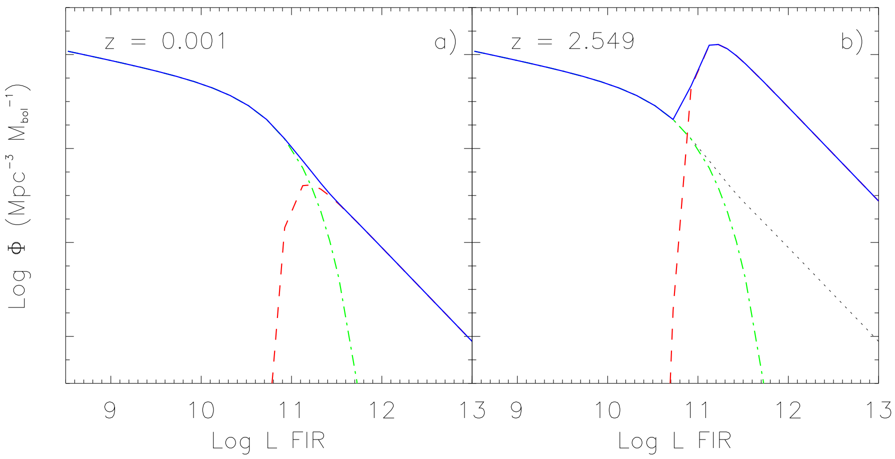

Fig. 4: Two snapshots of a model fitting the 175μm counts and the FIR background, taken from Dole et al. (2000). *a:* Luminosity Function at $z = 0$ (solid line); normal galaxy (dot-dash); ULIRG (dash-dash). *b*: Luminosity Function at $z = 2.5$ (solid line); normal galaxy (dot-dash) ULIRG (dash-dash) and local LF (dots).

Table 2: Provisional spectral classifications of ISO and 21cm selected sources in the Southern ELAIS field S1. Spectra come from a one hour 2dF exposure and a number of nights on the ESO 3.6m and NTT telescopes by Gruppioni et al. (in preparation) and by La Franca et al. (in preparation). Table taken from Oliver et al. (2000a).

Class	21cm		*ISO*	
	2dF	ESO	2dF	ESO
Absorption	48		15	6
Star-burst	9	3	22	52
Hα	5	2	26	
OII	10		4	
OIII	1			
AGN/QSO	6	2	20	19
AGN/Sy1	2	1	3	
AGN/Sy2	8	3	8	8
AGN/BLLac			2	
Stars	1		8	3
Too Faint	60	3	41	

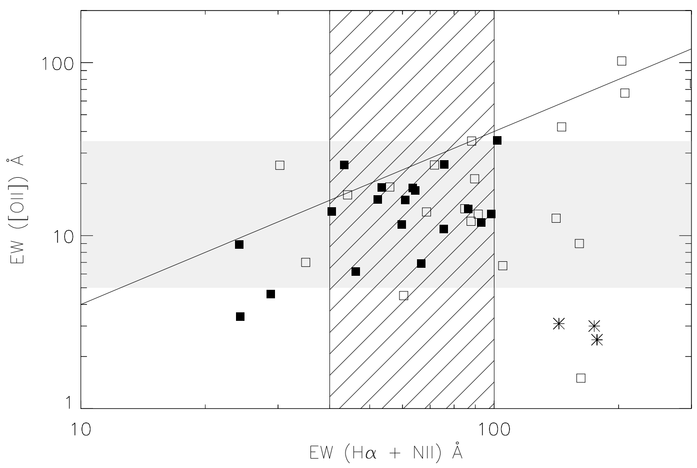

Fig. 5: EW(OII) vs. EW(Hα+NII), filled squares e(a) galaxies, open squares non–e(a) galaxies, stars Seyferts). The black line corresponds to EW(OII)=0.4 EW(Hα+NII) found for nearby field galaxies by Kennicutt (1992). The hatched vertical region shows the location of VLT measurements of the ISO–HDF-S galaxies, the shaded horizontal region the range from the ISO-CFRS sources. The intersection of the two bars represents the inferred location of the VLT ISO–HDF-S galaxies, indistinguishable from the dusty, luminous, e(a) galaxies. Figure taken from Rigopoulou et al. (2000).

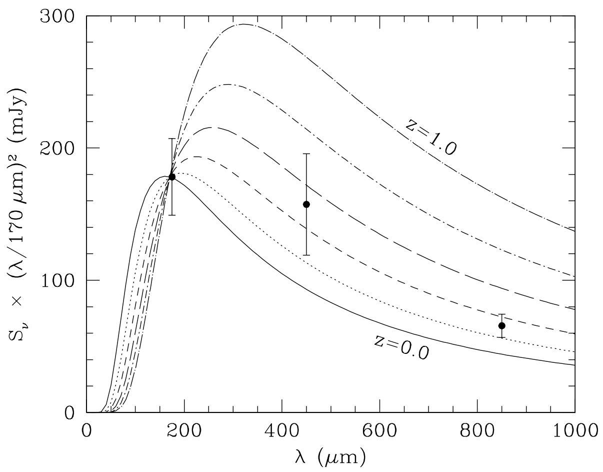

Fig. 6: Average spectral energy distribution for a FIRBACK sub-sample, from Scott et al. (2000). The 170μm point is the average of 10 FIRBACK sources, with error-bar being the standard error from the scatter among them. The 450μm and 850μm points are from SCUBA observations. For the sake of visual clarity y-axis has been multiplied by x^2. The curves show emission from modified blackbodies, normalized to the 170μm flux density, with $T_\mathrm{d} = 40\,\mathrm{K}$ and $\beta = 1.5$, and for $z = 0.0$ (solid line) up to $z = 1.0$ in steps of 0.2. Note that the shapes of these curves are degenerate in the combination $(1 + z)/T_\mathrm{d}$.

4. CONCLUSIONS

4.1 What ISO Source Counts Tell Us

- Strong significant evolution seen at all wavelengths observable to ISO.
- Differential 15μm counts appear to steepen and then decline below about 1 mJy.
- Source counts particularly steep at 175μm.
- ISO reached the confusion limit at all wavelengths, easily at the longest wavelengths.
- 10% of the FIR background was resolved at long wavelengths.
- As much as 30% of the FIR background may come from the sources detected at mid-IR wavelengths.
- Many models exist which might explain counts, though 175μm counts are harder to explain than other bands.

4.2 What ISO Survey Follow-up Tells Us

- Fainter mid-IR sources appear to be predominantly star-forming, rather than AGN.
- Brighter mid-IR sources may contain a higher fraction of AGN.
- Best current guess is that 175μm sources are $z < 1$ although based on limited evidence.

Forthcoming followup projects, notably X-ray surveys in ISO survey fields, should help enormously to identify what populations make up these strongly evolving ISO sources.

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