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Observations of the *Hubble Deep Field* with the *Infrared Space Observatory* – III. Source counts and $P(D)$ analysis

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**ABSTRACT**

We present source counts at 6.7 and 15 μm from our maps of the *Hubble Deep Field* (HDF) region, reaching 38.6 μJy at 6.7 μm and 255 μJy at 15 μm. These are the first ever extragalactic number counts to be presented at 6.7 μm, and are three decades fainter than *IRAS* at 12 μm. Both source counts and a $P(D)$ analysis suggest that we have reached the *Infrared Space Observatory (ISO)* confusion limit at 15 μm: this will have important implications for future space missions. These data provide an excellent reference point for other ongoing *ISO* surveys. A no-evolution model at 15 μm is ruled out at $\sigma > 3$, while two models which fit the steep *IRAS* 60-μm counts are acceptable. This provides important confirmation of the strong evolution seen in *IRAS* surveys. One of these models can then be ruled out from the 6.7-μm data.

**Key words:** surveys – galaxies: evolution – galaxies: formation – galaxies: Seyfert – galaxies: starburst – infrared: galaxies.

1 **INTRODUCTION**

*IRAS* galaxy surveys at 60 μm have consistently provided good evidence for a population of star-forming galaxies evolving with a strength comparable to that of active galactic nuclei. This has been confirmed by numerous studies of count distributions and redshift surveys from 0.6 Jy to 50 mJy (Hacking & Houck 1987; Saunders et al. 1990; Lonsdale, Hacking & Conrow 1990; Oliver et al. 1995; Gregorich et al. 1995; Bertin, Dennefeld & Moshir 1997).

This evolving population discovered by *IRAS* could have very important implications for cosmological studies. In particular, these objects are likely to contribute strongly to the star formation history of the Universe. Other incidental issues include the possibly significant impact that such objects could have on the cosmological far-infrared background: see e.g. Oliver, Rowan-Robinson & Sanders (1992) and Franceschini et al. (1991). The populations seen by *IRAS* are mostly relatively low-redshift ($z < 0.2$); deeper *Infrared Space Observatory (ISO)* surveys such as this provide a longer baseline in redshift, giving a better handle on the nature of the evolution.

This paper will discuss the source counts from our maps of the *Hubble Deep Field* (HDF: Williams et al. 1996). Our
observations have been described by Serjeant et al. (1997, Paper I), and the source extraction described by Goldschmidt et al. (1997, Paper II): a total of 27 sources were found at 6.7 \( \mu m \), and 22 at 15 \( \mu m \). Further papers discuss the associations with optical galaxies (Mann et al. 1997, hereafter Paper IV) and the models for spectral energy distributions and the star formation history (Rowan-Robinson et al. 1997, hereafter Paper V).

### 2 Observed Source Counts at 6.7 and 15 \( \mu m \)

In Paper II we detected seven sources in our 6.7-\( \mu m \) maps and 19 in our 15-\( \mu m \) maps using a well-defined source detection algorithm. To convert these source lists into source counts requires an estimate of the area within which a source of observed flux (\( S \)) could have been detected.

To estimate this we need to know the minimum flux (\( S_{\text{min}} \)) detectable at any position. The source detection algorithm requires \( m \) pixels to have intensity \( I(x,y) > T(x,y) \), where \( T(x,y) \) is the threshold intensity. The flux of resulting detections is estimated using an estimated local background intensity \( B(x,y) \). Assuming a well-determined point spread function (PSF), \( P(x-x_0, y-y_0) \), this algorithm gives us a detection limit

\[
S_{\text{lim}}(x_0, y_0) = \max_m \left[ \frac{T(x, y) - B(x, y)}{P(x-x_0, y-y_0)} \right],
\]

(1)

where \( \max_m \) is a function giving the \( m \)th largest value. \( T \) is defined for various areas in Paper II and \( B \) is determined by running the sky annulus across the full image.

The PSF is the only uncertainty in this estimate of the survey areas, and we thus decided to investigate this in some detail. One estimate for \( P \) comes from the standard ESA products. The PSF is estimated at 3 \( \times \) 3 sub-pixel positions for each filter and lens position. We drizzled these images together to produce a single PSF for each of our two observing modes. For both bands, the ESA PSF contains a large amount of flux in the wings. These wings may be caused by scattered light or other data reduction features in the ESA PSF. In any case, we cannot use the PSF for analysing the effective area, since only 20 per cent of the total flux is within the Airy disc, so we calculate a ‘revised’ ESA PSF which is background-subtracted in the same way as were the sources and normalized to 1 within the source aperture. Since our observations involved long integrations, in which jitter might significantly blur the PSF, and also because our data reduction did not take into account field distortions, we decided to estimate \( P \) empirically from the HDF observations themselves. \( P \) was estimated by summing the intensities from a number of sources in a square aperture 7 pixels to a side (i.e. 7 arcsec at 6.7 \( \mu m \) and 21 arcsec at 15 \( \mu m \)). The relatively small aperture at 6.7 \( \mu m \) was necessary to avoid including more than one source. At 15 \( \mu m \) we excluded objects near the boundaries and the fainter sources, leaving a sample of six sources, while at 6.7 \( \mu m \) we used all sources in the complete sample. We then normalized such that \( \sum P = 1 \) over the aperture. Some parameters of the PSFs discussed are summarized in Table 1.

Figs 1 and 2 show the effective areas of the surveys to sources of a given flux [\( \Omega(S_{\text{lim}} < S) \)]. Notice that the curves do not pass through the origin in Fig. 2; this is because the sources were detected using a fixed global threshold but the background is estimated locally, hence a source could in principle be detected in a high-background region but then assigned zero or even negative flux.

The faintest flux limit that can provide useful information is defined by the smallest usable area. We choose the smallest useful area to be 200 beams; using Figs 1 and 2 this translates to 38.6 and 255 \( \mu m \) over 1.6 \( \times \) 1.6 and 6.3 \( \times \) 6.3 arcmin\(^2\) respectively. These flux limits include six of the seven 6.7-\( \mu m \) sources and seventeen of the nineteen 15-\( \mu m \) sources. Allowing a smaller area of 40 beams would have suggested flux limits of 304 and 161 \( \mu m \), in which case the faintest 15-\( \mu m \) source would be excluded and the faintest 6.7-\( \mu m \) source would be at the flux limit.

At this point we can examine whether our HDF data approach the confusion limit of ISO. The maximum area available at 15 \( \mu m \) is around 18 \( \times \) 18 arcmin\(^2\), and thus the complete sample from Paper II of 19 sources is below the classical confusion limit (more than one source every 40 beams): see Fig. 2. As most of the complete 6.7-\( \mu m \) sample of seven objects have fluxes that are above 30.4 and 161 \( \mu m \), this is indicated by the curves in Figs 4 and 6 (in the HDF maps we can see seven 15-\( \mu m \) sources and seventeen of the nineteen 6.7-\( \mu m \) sources).

We use the areas determined with the empirical PSF to construct the observed differential source counts or integral counts:

\[
\frac{dN}{ds} = \frac{1}{\Omega(S_{\text{lim}} < S)}
\]

(2)

\[
N(S) = \frac{1}{\Omega(S)}
\]

(3)

The integral counts are shown in Figs 3 to 6 together with models and (in Figs 4 and 6) IRAS counts, which are discussed later. The integral counts are shown rather than differential counts, as these are more useful in practice; however, the data points are not independent and so Poisson 1e limits are shown as a hatched area. Rigorous statistical comparisons between data and models are best made by

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**Table 1. Characteristics of various point spread functions:**

| PSF        | \( P_{\text{max}} \) /arcsec\(^{-2} \) | FWHM /arcsec | \( S_{1D} \) | \( S_{\text{max}}(P) \) /arcsec\(^{-2} \) |
|------------|-----------------------------|-------------|------------|-----------------|
| ESA 6.7 \( \mu m \) | 0.038                      | 3.0         | 0.68       | 0.023           |
| Revised ESA 6.7 \( \mu m \) | 0.057                      | 3.0         | 1.00       | 0.094           |
| Empirical 6.7 \( \mu m \) | 0.051                      | 4.2         | 1.00       | 0.035           |
| ESA 15 \( \mu m \) | 3.0e-3                     | 5.4         | 0.20       | 7.0e-4          |
| Revised ESA 15 \( \mu m \) | 1.2e-2                     | 5.4         | 1.00       | 3.8e-3          |
| Empirical 15 \( \mu m \) | 6.2e-3                     | 10.0        | 1.00       | 3.4e-3          |
assessing the number of objects expected at given flux limits, and for this we apply the area as a function of flux to the model; these results are discussed in Section 4.4.

With the exception of the analysis of simulated data sets, we exclude objects in our complete list that are not associated with optical counterparts in Paper IV. This criterion removes one source at 6.7 μm and five at 15 μm.

3 STELLAR SOURCE COUNTS

Before moving on to discuss the galaxy counts, a brief word needs to be said about the stellar counts. At 6.7 μm there are no obvious stellar candidates in the complete sample. This is no real surprise, since the HDF was selected to exclude bright stars. Extrapolations from the models of Franceschini et al. (1991) predict 0.38 star arcmin$^{-2}$ for $S_\nu > 40 \, \mu$Jy at these latitudes, i.e. 1.9 stars if the HDF area was not biased against stars, reasonably consistent with our finding none. At 15 μm we see one stellar image in the flanking field (ISOHDF3 J123709.8 + 621239). The Franceschini et al. (1991) stellar model would predict 0.1 star arcmin$^{-2}$, i.e. around one to two stars in this field which is quite consistent with our single detection. This stellar object has been excluded from the galaxy counts.
we had to construct a mask to take account of the IRAS missing strip and regions of high source density that may have been excluded or under-represented. To this end we applied the Queen Mary and Westfield College IRAS Galaxy Catalogue (QIGC) mask (Rowan-Robinson et al. 1991); this cut excluded only 43 galaxies, reducing the sample to 850 objects, and provided an estimate of the area of 6.76 sr. These counts are shown in Figs 4 and 6.

4.1 IRAS galaxy counts

We can use the 12-μm IRAS galaxy counts to estimate the bright counts at 15 μm using the Rush, Malkan & Spinoglio (1993) sample. In order to estimate the area of this sample, we had to construct a mask to take account of the IRAS missing strip and regions of high source density that may have been excluded or under-represented. To this end we applied the Queen Mary and Westfield College IRAS Galaxy Catalogue (QIGC) mask (Rowan-Robinson et al. 1991); this cut excluded only 43 galaxies, reducing the sample to 850 objects, and provided an estimate of the area of 6.76 sr. These counts are shown in Figs 4 and 6.

Figure 3. 6.7-μm source counts from the HDF (hatched region). The models at 6.7 μm are based on Pearson & Rowan-Robinson (1996): all components, solid; normal galaxies, dotted; evolving starbursts, dash-triple-dotted; Seyferts 1 and 2, dashed and dot-dashed respectively. The depths probed by other, forthcoming ISO surveys are indicated (ELAIS, Oliver et al. 1997; CAM-D and CAM-S, e.g. Elbaz 1997; Taniguchi, Taniguchi et al. 1997).

Figure 4. 15-μm source counts from the HDF (hatched region), with IRAS 12 μm counts (thick line) at the bright end, from this paper and Rush et al. (1993) (IRAS data shifted to 15 μm using the cirrus spectrum). The models are based on Pearson & Rowan-Robinson (1996): all components, solid; normal galaxies, dotted; evolving starbursts, dash-triple-dotted; Seyferts 1 and 2, dashed and dot-dashed respectively. The depths probed by other, forthcoming ISO surveys are indicated (ELAIS, Oliver et al. 1997; CAM-D and CAM-S, e.g. Elbaz 1997).
4.2 Model galaxy populations

We consider two models of galaxy number counts. Both models have well-defined dust emission spectra, specifically to predict mid- to far-infrared galaxy distributions accurately. In addition, both models include strongly evolving components that are sufficient to explain the steep number counts at 60 μm. The specific populations and spectral energy distributions (SEDs) in the two models are, however, significantly different. Pearson & Rowan-Robinson (1996, hereafter PRR) have described a galaxy population model involving five populations: normal galaxies; starburst galaxies; hyper-luminous galaxies; Seyfert 1 galaxies; and Seyfert 2 galaxies. We have predicted the counts at 6.7, 12
and 15 μm using these models, ignoring the hyper-luminous population which will have a negligible contribution. Here, starbursts and normal galaxies have 60-μm luminosity functions taken from Saunders et al. (1990); the Seyfert 12-μm luminosity functions come from Rush et al. (1993). Both Seyferts and starbursts evolve as $L(z) = L(0)(1 + z)^{3.1}$. The SEDs used for these galaxies are based mainly on IRAS data and are described by Pearson & Rowan-Robinson (1996). The model assumes an $\Omega = 1$ cosmology. These models were shown to provide a good fit to the IRAS 60 μm counts. As they stand, these models would be unable to account for optical or K-band counts, but would require a low $\Omega$ or more strongly evolving starburst population. The integral counts predicted by this model are shown in Figs 3 and 4.

A second model comes from Franceschini et al. (1994, hereafter AF). The total counts are modelled as the sum of five populations: active galactic nuclei (AGN); starburst galaxies; spiral/irregular galaxies; SO galaxies; and elliptical galaxies. The late-type systems (spirals, irregulars and starbursts) evolve as $L(z) = L(0)e^{\tau z}$ (where $\tau$ is the look-back time), in an open universe ($q_0 = 0.15$). The early-type systems (ellipticals, SOs) evolve according to Franceschini et al. (1994), i.e. assuming that a bright phase of active star formation at $z \sim 2-4$ is obscured by dust quickly produced by the first stellar generations. This same model accounts in some way for the hyper-luminous population which will have a negligible contribution. Here, our positional errors are not significant excess, and may indicate either that our association requirements are too harsh or that our simulated noise is not realistic; improved understanding of the source counts at faint fluxes. The only remaining possible source of incompleteness is from uncertainties in our PSF, which may warrant further investigation.

The average numbers of sources detected from these simulations are listed in Tables 2 and 4 (see later). They do not appear to be significantly different from the model counts on which they are based. Although the simulations are carried out only for the first model, this has similar differential counts to the second at faint fluxes, so we would expect similar behaviour. In neither band do we see any appreciable discrepancies between the models and the simulations over the flux ranges including our data, and we conclude that any biases are small or cancel each other out.

4.4 Comparison of models

Using the area of the survey to a given flux limit (Figs 1 and 2), and the number count models of Section 4.2.1, we can estimate the number of sources of any given type that we would expect in this survey. These numbers are summarized in Tables 2–5. Both models are consistent with the total number of associated galaxies. The simulation at 15 μm predicts that there should be 8.37 objects, but our non-associated list includes 16 galaxies. This is a marginally significant excess, and may indicate either that our association requirements are too harsh or that our simulated noise is not realistic; improved understanding of the ISO data in the near future will clarify this. Interestingly, the PRR model predicts that a significant fraction (~70 per cent) of the objects should be at fluxes brighter than our brightest source. This discrepancy is also seen in the integral count plots (Fig. 3), where we can also see an apparent difference in slope between the model and the data.
To test whether discrepancies in the count slope are significant, we perform a Kolmogorov–Smirnov (KS) test to assess the probability of the observed fluxes being drawn from a count distribution with the same shape as the models (or single components of the models). These probabilities are given in Tables 2–5. These results suggest that the PRR model at 6.7 μm is ruled out with more than 99 per cent significance (using either the simulations or the raw models); this is mainly due to the expected fraction of bright objects. This model cannot be ruled out with more than 95 per cent confidence at the other wavelength, although the simulation implies a more significant discrepancy; this may again suggest problems with our simulations or association criteria.

In this test the AF model can also not be rejected with any high level of confidence (more than around 95 per cent) at either wavelength.

It thus appears that these data are insufficient to rule out either model at 15 μm. The PRR model can be ruled out at the shorter wavelength owing to the high fraction of bright galaxies predicted. It may be that revisions to the K-corrections of the ‘normal’ component using improved SEDs may be sufficient to improve this model. Possible problems with the ‘normal’ component SEDs are also suggested by the noticeable over-prediction of the IRAS 15-μm counts in the model.

A ‘no evolution’ version of the PRR starburst component would predict only 0.28 galaxies at 15 μm, i.e. 4.5 in total. Since we comfortably detect 11 galaxies, such a model can be ruled out at the 3σ level on integral counts alone.

### 5 P(D) Analysis

Since our maps are close to the ISO confusion limit, it is sensible to examine the low-level fluctuations in the maps on a statistical level. This allows us to investigate source count models below the flux level at which individual sources can be resolved. To this end, we explore the distribution of deviations in flux in a given aperture from the mean level, the P(D) distribution. This analysis avoids the need for any source detection algorithm. The fluctuations in a map about the mean intensity consist of two components. The first is the noise, which will have both positive and negative values, and will have some distribution function which we shall assume is Gaussian. The second component is true fluctuations. These might arise from sources, cosmo-
logical background or Galactic foreground. In all cases this contribution will always be positive and thus skew a symmetric noise distribution. In this case we assume that any major asymmetric component arises from extragalactic sources.

First we select sky regions and construct a histogram of flux deviations in square apertures. These histograms are fitted with both Gaussian distribution functions and the expected distribution functions from the source count models. These model distribution functions are calculated following Franceschini, Toffolatti & Danese (1989), and using the AF model for the source counts discussed above (the differential counts of this model are similar to those from the PRR model below the source detection limit, so the AF model results will be similar for both, and the model provides a better fit to the count distribution at 6.7 μm). The differential count distribution is first convolved with a model PSF (in this case a Gaussian PSF is assumed) to give the response function to single sources in the selected aperture. The $P(D)$ can then be calculated assuming that the sources are distributed on the sky as a Poisson process.

Fig. 7 shows the deflection distribution ($D$ in μJy) obtained from a $72 \times 72$ matrix of pixels derived from the inner portion of the drizzled mosaic of Paper I. We estimate a sky standard deviation in the inner map outside obvious sources of $\sigma = 16$–17 μJy aperture$^{-1}$ (dotted line in Fig. 7). The aperture is $6 \times 6$ arcsec$^2$ in area, enclosing a disc with a diameter equal to the FWHM of the theoretical PSF. The mean intensity is 0.4 mJy arcsec$^{-2}$.

The continuous thick line is the convolution of the Gaussian noise with a model $P(D)$ based on the counts appearing in Fig. 6. The convolved curve provides a very good fit to the data (reduced $\chi^2 \sim 1$). A simple Gaussian cannot fit the data, even if the width is increased to $\sigma = 18$–19 μJy aperture$^{-1}$ with reduced $\chi^2 > 1.5$. Thus there is a clear positive signal in the $P(D)$. This means that the background in an extremely deep ISO exposure at 15 μm is structured. Such structure is entirely consistent with being due to a smooth extrapolation of the ISO source counts observed above the flux threshold, and confirms the counts.

This $P(D)$ analysis allows us to constrain the models further. The shape of the AF model counts was fixed and the normalization allowed to vary. These constraints are illustrated in Fig. 6.

A similar analysis at 6.7 μm demonstrates that a simple Gaussian noise model is sufficient to provide a good fit to the observed $P(D)$. This allows only an upper limit on the normalization of the counts to be determined.

6 DISCUSSION OF POPULATIONS

So far we have not made any use of the fact that our survey was conducted in the Hubble Deep Field and Flanking Fields where there is exceptional photometric and spectroscopic information available. These data allow us to determine the populations detected by ISO. It is still instructive to compare observed and predicted populations, as this may provide clues for improvements to the models.

One of the 6.7-μm sources (ISOHDF J123646.4 + 621406) selected at 6.7 μm has broad emission lines (Paper...
IV). This is compatible with the predicted numbers of AGN in both of the models we have considered. Of the remaining four associated objects, only one is compatible with a normal cirrus spectrum galaxy and has an elliptical morphology; the others are better fitted with starburst spectra and have spiral morphologies (Paper V).

Excluding AGN, the first of the models (PRR) suggests that at 6.7 \( \mu \)m our sample should have a majority (71 per cent) of normal spiral galaxies with around 28 per cent of starburst galaxies. The expected probability of obtaining the observed one or fewer cirrus galaxies in a sample of four is \( \sim 7 \) per cent. Although the statistics are very poor, this casts further doubt on the validity of the PRR model at this wavelength. The classification of SEDs in Paper V is based mainly on the optical/infrared luminosities. Extra information comes from the expected redshift distribution of these normal galaxies and starbursts, which is shown in Fig. 8. A KS test cannot rule out the possibility that the observed redshifts are drawn from the model distribution even if the redshift of the broad-lined object is included: the probability of the data being drawn from the model distribution is 0.18.

Paper V does not attempt to fit SEDs of the type used for the second model. However, this model predicts that the non-AGN 6.7-\( \mu \)m sources would be 61 per cent ellipticals or S0s and 39 per cent spirals. This is reasonably consistent with the morphologies and SEDs above.

Only three of the 15-\( \mu \)m-selected sources are associated within the HDF itself. Two of these have spiral morphologies and are fitted by starburst spectra, while the third has elliptical morphology and a cirrus spectrum. With such limited statistics this is reasonably compatible with both models. Including the Flanking Field areas, we find in Paper IV that six of the 15-\( \mu \)m-selected sources have associations and redshifts (or photometric redshifts). These are shown in Fig. 9 together with the redshift distribution from the PRR model. Excluding the lowest redshift object (which was excluded from our count analysis as being below the 255-mJy flux limit that was also applied to our model redshift distributions), we find that we cannot rule out these redshifts being drawn from this expected distribution (probability 0.41). This test is hampered by small-number statistics, but also assumes that the objects in the Flanking Fields with redshifts are not biased in any way. Clearly, obtaining spectra for the Flanking Field 15-\( \mu \)m sources is a high priority.

7 IMPLICATIONS FOR FUTURE SURVEYS AND MISSIONS

The fact that we have reached the ISO confusion limit at 15 \( \mu \)m with a sensitivity of around 0.2 mJy has important implications for other surveys and missions, in particular NASA’s Small Explorer Mission, the Wide-Field Infrared Explorer (WIRE, http://www.ipac.caltech.edu/wire/). WIRE is due for launch in 1998 September and plans to survey hundreds of square degrees at 12 and 25 \( \mu \)m. The WIRE strategy is divided into three parts: Part I – a moderate-depth survey (60 per cent of the survey time); Part II – a deep, confusion-limited survey (30 per cent of the survey time); and Part III – an ultra-deep, confusion-distribution measurement. The areal coverage and integration times will be designed to achieve these aims, and so the best estimate of the confusion limit is required prior to planning. Currently the WIRE team estimate confusion limits of between 0.067 and 0.15 mJy at 12 \( \mu \)m (http://www.ipac.caltech.edu/wire/sensitiv.html), depending on the evolutionary models. WIRE has a 30-cm mirror with

![Figure 8](image_url)
Figure 9. Expected redshift distribution at 15 μm within the ISO HDF areas (accounting for the area-dependent flux limit) for the starburst and cirrus components of the PRR model. Overplotted at arbitrary y-position are the redshifts for the six objects with reliable associations and spectroscopic or photometric redshifts in Paper IV; the lowest redshift object has the lowest flux and was excluded from our count analysis. The probability that these data are drawn from the expected distribution estimated using the KS test is 0.41, excluding the lowest z object.

Further information on the ISO HDF project can be found on the ISO HDF World Wide Web page (http://artemis.ph.ic.ac.uk/hdf/).

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