Observations of the *Hubble Deep Field* with the *Infrared Space Observatory* - IV. Association of sources with *Hubble Deep Field* galaxies

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Observations of the *Hubble Deep Field* with the *Infrared Space Observatory* – IV. Association of sources with *Hubble Deep Field* galaxies

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ABSTRACT

We discuss the identification of sources detected by the *Infrared Space Observatory* (*ISO*) at 6.7 and 15 μm in the *Hubble Deep Field* (HDF) region. We conservatively associate *ISO* sources with objects in existing optical and near-infrared HDF catalogues using the likelihood ratio method, confirming these results (and, in one case, clarifying them) with independent visual searches. We find 15 *ISO* sources to be reliably associated with bright [$I_{814}(AB)<23$] galaxies in the HDF, and one with an $I_{814}(AB)=19.9$ star, while a further 11 are associated with objects in the *Hubble Flanking Fields* (10 galaxies and one star). Amongst optically bright HDF galaxies, *ISO* tends to detect luminous, star-forming galaxies at fairly high redshift and with disturbed morphologies, in preference to nearby ellipticals.

Key words: galaxies: evolution – galaxies: starburst – infrared: galaxies.

1 INTRODUCTION

This series of papers describes a set of very deep mid-infrared observations, obtained using the ISOCAM (Cesarsky et al. 1996) instrument on the *Infrared Space Observatory* (*ISO*: Kessler et al. 1996) and centred on the *Hubble Deep Field* (HDF: Williams et al. 1996) region. In Paper I (Serjeant et al. 1997) we discussed the reduction of the ISOCAM data and presented the resultant maps of the HDF region at 6.7 and 15 μm. Paper II (Goldschmidt et al. 1997) described the methods that we used for detecting sources in these maps, while Paper III (Oliver et al. 1997) compared source counts derived from these detections with model predictions. The two principal goals of this paper are to confirm the *ISO* HDF sources, through associating them with objects in existing HDF galaxy catalogues, and to study the properties of those associated galaxies, contrasting them with those of bright HDF galaxies not detected by *ISO*. The spectral energy distributions resulting from the association procedure will be discussed in Paper V (Rowan-Robinson et al. 1997), together with their implications for the star formation history of the Universe.

The plan of this paper is as follows. In Section 2, we briefly review the basic problems we face in associating the *ISO* HDF sources with galaxies in existing HDF catalogues. The likelihood ratio method for source identification is described in Section 3, where we present the results of applying it to our *ISO* HDF sources and discuss the reliability of the associations that we made using it. In Section 4 we discuss the properties of the galaxies associated with our

ISO sources, as well as those prominent optical HDF galaxies that we did not detect, and present the conclusions that we draw from the work described in this paper.

2 *ISO* SOURCE DETECTIONS IN THE *HUBBLE DEEP FIELD*

A total of 27 sources (seven in the complete sample, and 20 in the supplementary sample) were detected in the 6.7-μm map, together with 22 sources (19 complete, three supplementary) at 15 μm: the positions and fluxes of these objects are tabulated in Paper II.

There are several basic problems which complicate the association of *ISO* HDF sources with HDF galaxies in existing optical and near-infrared catalogues. The most obvious of these is the poor match between the resolution of ISOCAM and the high source density of galaxies in the HDF: the radius of the Airy disc is 2.8 arcsec at 6.7-μm and 6.0 arcsec at 15 μm, while there are several hundred galaxies per square arcmin detected to $I_{814} \sim 29$, so we expect several galaxies per randomly placed Airy disc at both 6.7 and 15 μm. [N.B. Unless otherwise stated, the magnitudes used in this paper are total magnitudes in the *AB* system, as measured by Williams et al. (1996), and we follow them in denoting their four optical bands as U_{300}, B_{450}, V_{606} and I_{814} to avoid confusion with the standard Johnson photometric bands.] Thus not only is there a high likelihood of chance associations with optical galaxies, but any given ISOCAM beam may be integrating over more than one source, and significant flux may be contributed by more than one galaxy: this latter is exacerbated both because many luminous mid-infrared sources are likely to be interacting or merging galaxy systems (e.g. Lawrence et al. 1989), and by the fact that our *ISO* maps appear to be at, or close to, the confusion limit in both bands (Paper I). An additional positional uncertainty results from the possibility of field distortions in the original *ISO* data (Paper I). We make some allowance for this in our source association procedure (see Section 3), and feel that it is unlikely to affect our results significantly. Another issue is the band in which to make the associations, since, clearly, the wide range of colours exhibited by HDF galaxies could mean that different galaxies would be associated with a particular *ISO* source in different bands, and an unfortunate choice of band could bias the associations made: for example, we might expect the true counterparts of our *ISO* galaxies to be dusty, so using too blue a band might lead us to make the wrong associations. With that in mind we have performed the likelihood ratio procedure of Section 3 on the I_{814} images of Williams et al. (1996), as I_{814} is both the reddest and deepest band, as well as the only one available in the *Hubble Flanking Fields* (HFF). Finally, we have relatively few sources (only 19 of the 6.7-μm sources and five of those at 15 μm have Airy discs that fall within the HDF), restricting our ability to use statistical techniques which rely on the determination of properties of the source population from the data themselves.

As a first step towards our goals, we compare the I_{814}-band magnitude distribution of galaxies near our *ISO* HDF source positions with that of the complete optical HDF galaxy catalogue of Williams et al. (1996). In Fig. 1 we plot the I_{814}-band magnitude distribution of those HDF galaxies within twice the Airy disc radius of the nineteen 6.7-μm *ISO* HDF source positions lying within the HDF, together with that for the full Williams et al. (1996) optical galaxy catalogue. The histogram for the *ISO* HDF neighbours is noisy, both because of the small number of sources, and because a number of them lie close to the edge of the HDF, and the correction made for the fraction of the search region outside the HDF can give large weights to those HDF galaxies inside it. It is clear from Fig. 1 that there is an excess of bright ($I_{814} < 23$) galaxies surrounding our *ISO* HDF source positions: a two-sided Kolmogorov–Smirnov test yields a probability $P = 1.6 \times 10^{-3}$ that the two magnitude distributions are drawn from the same population (falling to $P = 5.4 \times 10^{-4}$ when only the six sources from the complete 6.7-μm sample are considered), and the five 15-μm sources in the HDF yield similar results. This strongly suggests that the sources in our *ISO* HDF samples are associated with bright galaxies in the HDF.

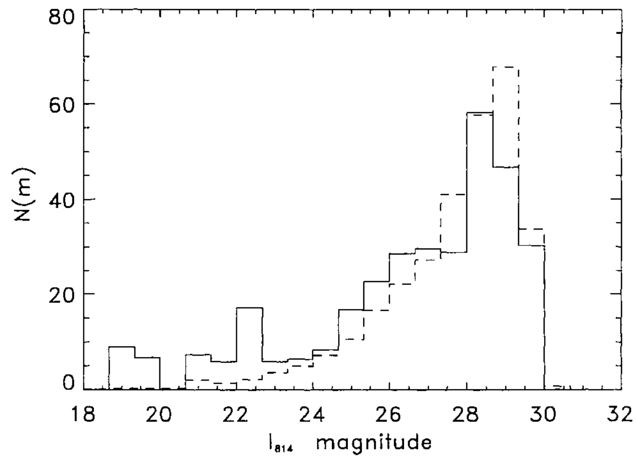

Figure 1. I_{814}-band magnitude histograms for galaxies near *ISO* HDF 6.7-μm source positions, and for the whole Williams et al. (1996) catalogue. The solid histogram shows the magnituded distribution of galaxies lying within twice the Airy disc radius of the nineteen 6.7 μm sources whose Airy discs fall within the HDF, while the dashed histogram traces the magnitude distribution for the full HDF catalogue, normalized to the total area enclosed by the 19 Airy discs. There is a clear excess of bright galaxies surrounding the *ISO* HDF sources.

3 ASSOCIATING *ISO* HDF SOURCES USING THE LIKELIHOOD RATIO METHOD

3.1 The likelihood ratio method

The likelihood ratio method is one of the most commonly used techniques for associating *sources* in one catalogue with *objects* in another: it is described in detail by Sutherland & Saunders (1992), so we present only a brief review here. The likelihood ratio, *LR*, is defined to be the ratio of the probability, $p_{\rm true}$, of finding the true counterpart to the source at the position of the object and with its flux, to the probability, $p_{\rm chance}$, of finding a chance object at that position and with that flux, given the errors in the source and object positions. Consider an object with positional offsets (x, y) from the estimated source position and with flux f. The probability that the true counterpart lies in an infinitesimal region of area $dx\,dy$ about that position, and has a flux in an infinitesimal interval of size df about that flux, is given by

$$p_{\rm true} = q(f)\,e(x,y)\;df\;dx\;dy, \qquad (1)$$

where $e(x,y)$ is the joint probability distribution function for x and y, normalized so that $\int e(x,y)\,dx\,dy = 1$ and $q(f)$ is the probability distribution function for an ensemble of sources, measured in the passband in which the object catalogue is defined. If $n(f)$ is the local surface density of objects per unit flux, then $p_{\rm chance} = n(f)\,df\,dx\,dy$ and LR is given by

$$LR(f,x,y) = \frac{q(f)\,e(x,y)}{n(f)}. \qquad (2)$$

To implement this method to associate *ISO* HDF sources with objects in the STScI HDF optical catalogue (Williams et al. 1996), we make the following assumptions concerning the quantities present in equation (2). We neglect the uncertainties in the optical positions, setting $e(x,y)$ equal to a Gaussian distribution, with a σ-value equal to the quadrature sum of the radius of the Airy disc for the *ISO* sources (2.8 arcsec at 6.7 μm and 6.0 arcsec at 15 μm) and an estimated positional error of equal size: this is a crude estimate of the true positional uncertainties, designed, in part, to take account of the possibility of ISOCAM field distortions, but the associations made are insensitive to variation of this figure within reasonable bounds. The form of $n(f)$, which is the magnitude distribution of the galaxies in the I_{814} band, is readily computed, but the choice of $q(f)$ is more problematic. As discussed by Sutherland & Saunders (1992), the two conventional approaches would involve assuming some model for the magnitude distribution of the true optical counterparts of our *ISO* HDF sources, or estimating $q(f)$ from the data, which, essentially, means taking the difference between the pair of histograms shown in Fig. 1. The latter method would, clearly, yield an unsatisfactorily noisy $q(f)$ (particularly for the 15 μm sources), while sufficiently little is known about the mid-infrared properties of the galaxies that we are likely to detect with *ISO* in the HDF that adopting a model based, say, on *IRAS* data could seriously bias our results. We choose, instead, to take $q(f)$ equal to a constant, independent of magnitude: uncertainty as to the exact reliability of our *ISO* samples means that the value this constant should take remains unclear, so that the likelihood ratios we compute are left unnormalized, proportional to those defined by equation (2). This uniform $q(f)$ is no doubt incorrect, since, on the evidence of Fig. 1 (as well as a priori prejudice), the galaxies that we detect are likely to be amongst the brightest in the HDF. Its effect, given that point, is to make us more likely to identify our *ISO* sources with fainter galaxies than we should. In fact, as we shall see, our associations are with bright galaxies, which suggests that our taking a uniform $q(f)$ has not biased our results.

3.2 Results

Deciding what level of likelihood ratio we consider to correspond to a reliable association is a somewhat subjective matter. Independently of the applications of the likelihood ratio technique, two of us (RGM and MRR) made independent associations by eye, using I_{814} images of the HDF fields, with the Airy discs of the *ISO* HDF sources superimposed upon them. In making these associations we are likely to have been making a subconscious balance between the brightness of a given galaxy and its distance from the source position, qualitatively similar to the likelihood ratio method, where $LR \propto e(x,y)/n(f)$. Nevertheless, the level of agreement obtained, both between the two observers and with the results of the likelihood ratio analysis, is surprising: for all but one source the two observers agreed on the most likely association, and the sources that they felt confident in having associated reliably were in a one-to-one correspondence with the sources yielding the highest likelihood ratios.

We can estimate the level of reliability of these associations by considering the likelihood ratios for association with random points in the HDF. In Fig. 2 we show the cumulative probability distribution for the likelihood ratio of the most likely HDF galaxy for being the optical counterpart of a fictitious 6.7-μm source at a random position in the HDF, computed using the same forms for $q(f)$ and $n(f)$ as for the *ISO* HDF sources and 10 000 random positions in the HDF. From Fig. 2 we can compute, as a function of LR, the quantity $P_{\rm ran}(I_{814})$, which is the probability that a fictitious source, placed at random in the HDF, would have a likeliest association in the I_{814} catalogue of Williams et al. (1996) with a likelihood ratio at least as high as a given value of LR. The $P_{\rm ran}$ value for the best optical candidates for the 6.7-μm sources marking the boundary above which the observers conservatively considered their associations to be reliable was about $P_{\rm ran} = 0.35$. We chose this conservative level to mark the break between those associations that we consider to be reliable and those that we do not.

In Table 1 we list the properties of the HDF galaxies that are our preferred associations for the 15 *ISO* HDF sources that we take as having reliable associations in the HDF region: these data are used to compute the spectral energy distributions of the galaxies in Paper V.

The same procedure was then applied to an I_{814}-band HFF catalogue, resulting in the association of a further 11 *ISO* HDF sources with HFF objects (10 galaxies and one star): the construction of this catalogue is described in the Appendix, where the HFF associations are tabulated. These

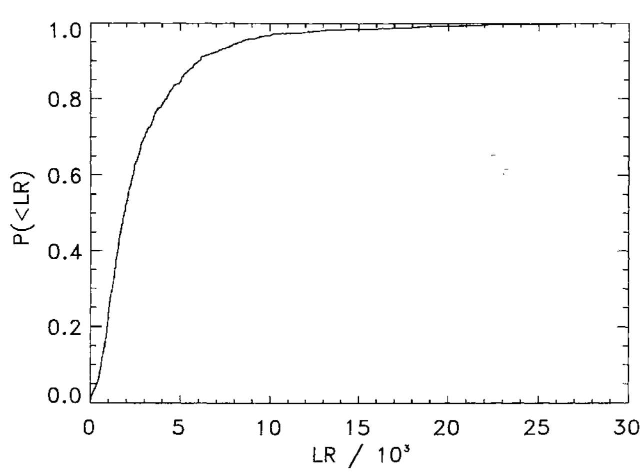

Figure 2. The cumulative probability distribution for the likelihood ratio of the likeliest optical counterpart to a fictitious 6.7-μm source placed at random in the HDF.

Table 1. Properties of the galaxies reliably associated with the *ISO* HDF sources in the *Hubble Deep Field*.

ISO Source	ST	RA	Dec	$P_{\rm ran}(I_{814})$	U_{300}	B_{450}	V_{606}	I_{814}	IfA	J	$H+K$	6.7μm	15μm	8.4 GHz	z
J123641.1+621129 3C	4-976.0	41.64	11 31.9	0.031	21.23	20.33	19.96	19.71	-	-	-	< 89.5	376	-	(0.047)
J123641.6+621142 2S	4-948.0	41.31	11 40.9	0.083	24.96	23.76	23.00	22.04	-	-	-	51.6	265	-	0.585
J123642.6+621210 2S	4-656.0	42.91	12 16.3	0.322	22.81	22.17	21.27	20.70	11	20.15	20.22	22.9	< 287	-	0.454
J123642.9+621309 2S	1-57.0	42.72	13 07.3	0.061	24.64	23.94	22.91	21.94	-	-	-	51.1	< 170	-	(0.737)
J123643.0+621152 2C	4-775.0	43.18	11 48.0	0.407	25.94	24.85	23.87	22.45	20	20.90	20.67	57.9	< 336	-	(0.820)
J123643.7+621255 3C	4-402.0	44.19	12 47.9	0.199	22.48	21.90	21.13	20.45	32	19.90	19.87	< 43.2	319	13.0	0.558
J123643.9+621130 2S	4-752.0	44.38	11 33.2	0.203	25.51	25.32	23.08	21.31	-	-	-	50.4	< 225	458.0	1.013
J123646.4+621406 2C	2-251.0	46.34	14 04.6	0.093	25.29	23.64	22.49	21.32	9	20.07	20.04	52.1	< 361	152.0	0.960
J123648.1+621432 3C	2-537.0	48.33	14 26.4	0.031	21.11	20.09	19.49	19.19	-	-	-	49.8	231	-	(0.023)
J123648.2+621427 2C	2-537.0	48.33	14 26.4	0.002	21.11	20.09	19.49	19.19	-	-	-	65.7	< 243	-	(0.023)
J123648.4+621215 2C	4-260.111	48.24	12 13.6	0.207	24.16	23.84	23.52	22.67	45	21.82	21.79	51.2	< 295	-	(0.778)
J123649.7+621315 2C	2-264.1	49.76	13 13.1	0.080	24.92	23.48	22.24	21.46	17	20.61	20.28	48.1	440	22.0	0.475
J123649.8+621319 3C	2-264.1	49.76	13 13.1	0.337	24.92	23.38	22.24	21.46	17	20.61	20.28	52.3	472	22.0	0.475
J123651.5+621357 3S	2-652.0	51.78	13 53.7	0.063	23.96	22.96	21.94	21.08	10	20.23	20.00	< 51.4	155	-	0.557
J123658.9+621248 2S	3-534.0	58.76	12 52.3	0.262	22.99	22.35	21.58	21.18	27	20.63	20.60	43.1	< 279	-	0.320

Notes to Table 1. The first column gives the *ISO* source name, as listed in Paper II, minus 'ISOHDF' and the prefix indicating in which band the source was detected. This latter information is indicated by '2' (LW2 filter, 6.7 μm) and '3' (LW3 filter, 15 μm) following the source name: 'C' or 'S' indicates whether the *ISO* source comes from the complete or supplementary sample for that waveband. The next column lists the name of the preferred associated optical galaxy from Williams et al. (1996), which is followed by its position in J2000 coordinates, with $12^{\rm h}36^{\rm m}$ and $+62°$ subtracted from the RAs and Dec.s, respectively. The fifth column gives the value of $P_{\rm ran}(I_{814})$ for the association. The next four columns give the total magnitudes of the associated galaxy in the U_{300}, B_{450}, V_{606} and I_{814} bands, respectively, computed using the total V_{606} magnitudes from Williams et al. (1996) and their $B_{450}-V_{606}$, $U_{300}-B_{450}$ and $V_{606}-I_{814}$ colours. The column headed 'IfA' gives the entry number of the associated galaxy in the Songaila (1997) catalogue, which is followed by the total J and $H+K$ magnitudes for the galaxy, computed from the aperture magnitudes given by Songaila (1997), using the I_{814} magnitudes given for the galaxies by Songaila (1997) and Williams et al. (1996), under the assumption that the galaxies do not possess significant colour gradients in their outer regions: this assumption is perfectly adequate for our present purposes. All magnitudes are quoted in the *AB* system. The *ISO* fluxes and 2σ upper limits at 6.7 and 15 μm are in μJy and are as tabulated in Paper II. The 8.4-GHz radio fluxes are in units of μJy and are taken from Fomalont et al. (1997). Spectroscopic redshifts are taken from the compilation by Cohen et al. (1996), except for the redshift for ST4-948.0, which comes from Phillips et al. (1997): values in parentheses are photometric redshifts calculated according to the method of Mobasher et al. (1996). This set of data is used to compute the spectral energy distributions of the galaxies in Paper V. One reliable association is omitted: ISOHDF2 J123647.1 + 621426 (ST2-381.0) is a star, and is discussed further in the text.

results, taken together, provide lower limits to the reliability of the four *ISO* HDF samples; lower limits because we have been conservative in accepting associations as reliable, and a substantial number of further associations fall just below our threshold, and might rise above it, for example, once more is known of the field distortions in ISOCAM data. The 6.7- and 15-μm complete samples are at least 71 and 68 per cent reliable, respectively, while the reliabilities of the supplementary 6.7- and 15-μm samples are no worse than 35 and 67 per cent respectively.

3.3 Notes on individual associations

In this subsection we discuss in detail the associations presented in Table 1: these comments should be borne in mind when using the results of Table 1. In what follows, galaxies in the I_{814} HDF image are denoted by the names assigned by Williams et al. (1996), prefixed by 'ST', while those from the $H+K$ image of Cowie et al. (in preparation) are denoted by their number in the catalogue of Songaila (1997), with the prefix 'IfA', and photometric redshifts have been computed using the method of Mobasher et al. (1996), without using the *ISO* data themselves.

(i) **ISOHDF3 J123641.1 + 621129.** The position of this 15-μm source falls just inside the HFF, but it is included here because its Airy disc encloses the very bright galaxy ST4-976.0, with which we have associated it: its proximity to the edge of the HDF means that ST4-976.0 has no counterpart in the Songaila (1997) catalogue, and we have estimated a photometric redshift of $z=0.047$ for it.

(ii) **ISOHDF2 J123641.6 + 621142.** This is associated with the brighter member (ST4-948.0) of a merging pair of galaxies, which is too near the edge of the HDF to be included in the near-infrared catalogue of Songaila (1997), despite appearing bright in both the J and $H+K$ images of Cowie et al. (in preparation). Phillips et al. (1997) report a spectroscopic redshift of $z=0.585$ for ST4-948.0.

(iii) **ISOHDF2 J123642.6 + 621210.** This source falls mid-way between two spiral galaxies: ST4-656.0/IfA11 ($z=0.454$: Songaila 1997) and ST4-795.0/IfA14 ($z=0.432$: Songaila 1997). It is associated with the former, which is brighter and yields a higher likelihood ratio, but note that this is one of the least reliable of our accepted associations.

(iv) **ISOHDF2 J123642.9 + 621309.** This interacting pair (ST1-57.0 is the brighter member) falls in the Planetary Camera HDF field, and so is not included in the Songaila (1997) catalogue. We estimate a photometric redshift of $z=0.737$ for ST1-57.0.

(v) **ISOHDF2 J123643.0 + 621152.** This source may have flux contributed by ST4-727.0/IfA59, as well as ST4-775.0/IfA20, as listed in Table 1. ST4-727.0/IfA59 is half a magnitude fainter in I_{814} than ST4-775.0/IfA20, but is closer to the *ISO* position, and so yields a lower value of $P_{\rm ran}(I_{814})$: $P_{\rm ran}(I_{814})=0.269$ as against $P_{\rm ran}(I_{814})=0.407$ for ST4-775.0/IfA20. Despite that, we conservatively take ST4-775.0/IfA20 as being the association, on the basis of its lower photometric redshift: $z=0.820$, versus $z=1.63$ for ST4-727.0/IfA59. Having two galaxies with such low $P_{\rm ran}(I_{814})$ values clearly breaks the assumption, implicit in the likelihood ratio method, that there is not more than one true optical counterpart to each *ISO* source, which gives some justification for over-riding our reliability criterion that $P_{\rm ran}(I_{814})<0.35$ in this one case.

(vi) **ISOHDF3 J123643.7 + 621255.** This is associated with the brighter member (ST4-402.0/IfA32) of an interacting pair of galaxies on the basis of extremely reliable I_{814} data: $P_{\rm ran}(I_{814})=0.025$. Cohen et al. (1996) give a spectroscopic redshift of $z=0.558$ for this galaxy.

(vii) **ISOHDF2 J123643.9 + 621130.** ST4-752.0 has an acceptable $P_{\rm ran}(I_{814})$ value. It is too close to the edge of the HDF to have been included in the Songaila (1997) catalogue, although it looks bright in both the J and $H+K$ images of Cowie et al. (in preparation). A spectroscopic redshift of $z=1.013$ is given for ST4-752.0 by Cohen et al. (1996).

(viii) **ISOHDF2 J123646.4 + 621406.** This source is confidently associated with ST2-251.0/IfA9: there are no plausible alternative associations. Cohen et al. (1996) quote a spectroscopic redshift of $z=0.960$ for this galaxy, and the broad emission lines in the spectrum shown by Songaila (1997) indicate that this galaxy hosts an AGN.

(ix) **ISOHDF2 J123647.1 + 621426.** This is identified as a stellar object (ST2-381.0). The V_{606}, I_{814}, J and $H+K$ magnitudes can be fitted very well with a $T=3450$ K blackbody, so this appears to be an M0 star. The corresponding predicted flux at 6.7 μm would be 15 μJy, a factor of 2 lower than we observe, so we must presume that the star has a circumstellar dust shell, perhaps analogous to U Aur (Rowan-Robinson & Harris 1982).

(x) **ISOHDF3 J123648.1 + 621432.** This source is just outside the HDF, but is included here because we have confidently associated it with a bright HDF galaxy (ST2-537.0): this galaxy is not included in the Songaila (1997) catalogue, because it is at the edge of the HDF. We estimate a photometric redshift of $z=0.023$ for this galaxy, using the methods of Mobasher et al. (1996).

(xi) **ISOHDF2 J123648.2 + 621427.** ST2-437.0 is clipped off the edge of the Cowie et al. (in preparation) $H+K$ image: the (photometric) redshift for this galaxy is $z=0.023$, as given above.

(xii) **ISOHDF2 J123648.4 + 621215.** The flux from this source may be a combination of that from ST4-186.0/IfA44, an elliptical galaxy, and that from our preferred choice of ST4-260.11/IfA45, which is a spiral galaxy with a bright giant H II region. We favour the latter on the conservative basis of its having a lower photometric redshift ($z=0.778$ versus $z=1.512$), but note that both galaxies may contribute flux to this source.

(xiii) **ISOHDF2 J123649.7 + 621315.** This source falls within a small group of bright galaxies, which are probably not physically associated. ST2-264.1/IfA17 is the preferred association for ISOHDF2 J123649.7 + 621315, although it is possible that this source also includes flux from ST2-256.0/IfA43 and ST2-239.0/IfA35. ST2-264.1/IfA17 has a spectroscopic redshift of $z=0.475$ (Cohen et al. 1996).

(xiv) **ISOHDF3 J123649.8 + 621319.** This source lies in the same group of galaxies as ISOHDF2 J123649.7 + 621315 and, as with that source, we favour ST2-264.1/IfA17 as the most likely association, but note that it is likely that this 15-μm source includes flux from ST2-256.0/IfA43 and ST2-239.0/IfA35, as well as, perhaps, ST2-404.0/IfA6. As noted above, Cohen et al. (1996) quote a spectroscopic redshift of $z=0.475$ for ST2-264.1/IfA17.

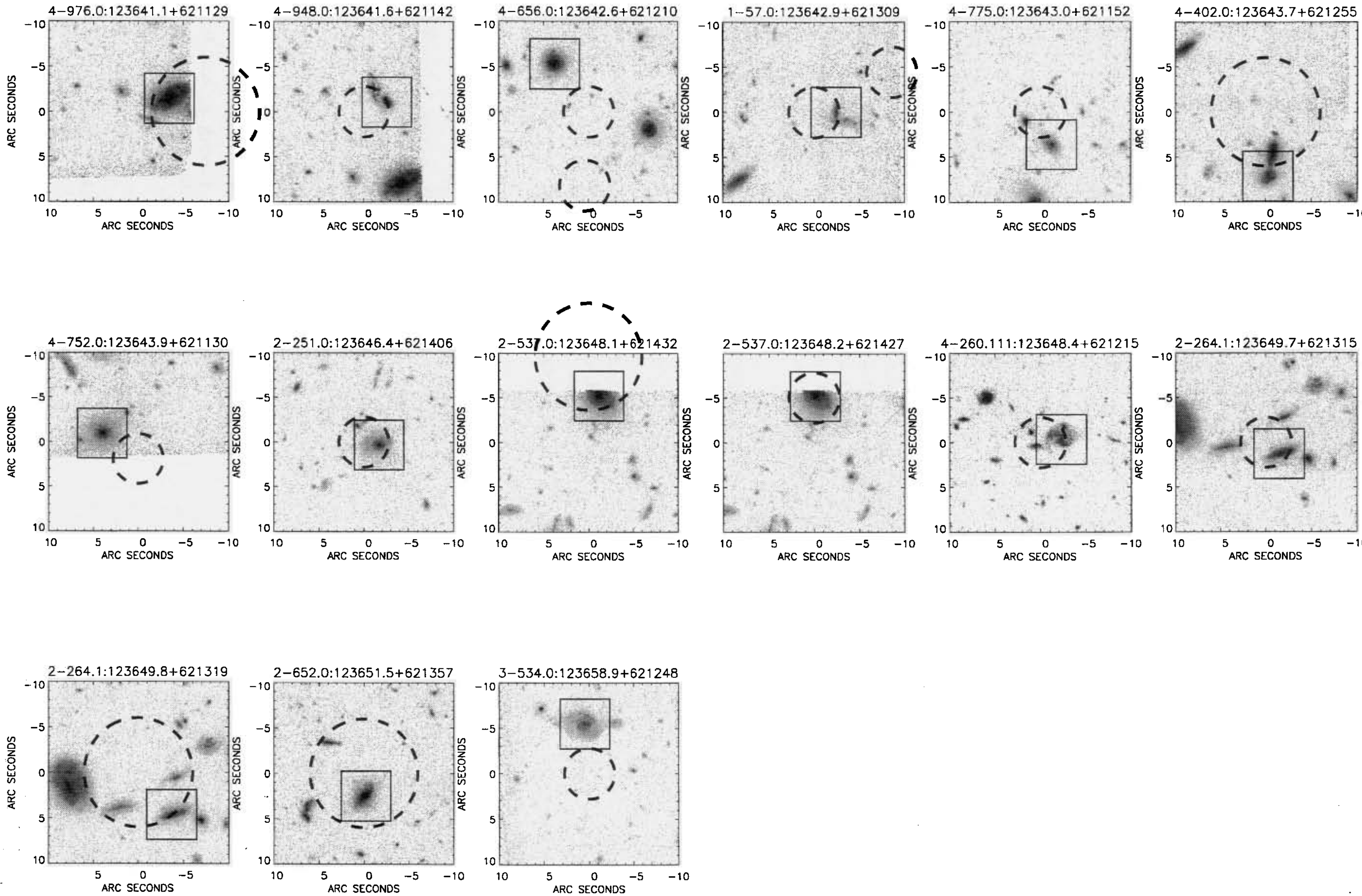

Figure 3. Positions of *ISO* HDF sources and their associations, from a I_{814}-band mosaic of the HDF. Dashed circles show the Airy discs of the *ISO* HDF sources; squares mark the positions of the associated optical galaxies; a second dashed circle indicates a second source from the same sample nearby. Where the *ISO* source position falls within the HDF, the plots are centred on those positions; in three cases the source falls just outside the HDF and the Airy disc is displaced from the centre of the plot. The title to each plot gives the name of the *ISO* source and the Williams et al. (1996) name for the optical galaxy associated with it.

(xv) **ISOHDF3 J123651.5 + 621357.** This is associated with ST2-652.0/IfA10: Cohen et al. (1996) give the spectroscopic redshift of ST2-652.0/IfA10 as $z = 0.557$.

(xvi) **ISOHDF2 J123658.9 + 621248.** This source is associated with ST3-534.0/IfA27: there are no plausible alternative associations, and Cohen et al. (1996) have determined its redshift spectroscopically to be $z = 0.320$.

In Fig. 3 we show the immediate surroundings (in an I_{814}-band mosaic) of the 15 *ISO* HDF sources reliably associated with HDF galaxies. The dashed circle in the centre of each plot marks the Airy disc of the *ISO* source, and the square is centred on the position in the optical catalogue of Williams et al. (1996) of the galaxy with which we have associated it. For those plots where the edge of the HDF is within the frame, the *ISO* HDF source position is no longer placed at the centre of the plot, while the presence of a second circle in the same field indicates the Airy disc of another *ISO* HDF source from the same sample. Three-colour (B_{450}, V_{606}, I_{814}) versions of these plots can be viewed at http://artemis.ph.ic.ac.uk/hdf/catalogue.html.

3.4 Sources not reliably associated

Twenty two *ISO* HDF sources have not been reliably associated with stars or galaxies in the optical HDF catalogue of Williams et al. (1996) or in our own HFF catalogue: in (i) the complete 6.7-μm sample (123655.1 + 621423 and 123658.8 + 621313); (ii) the supplementary 6.7-μm sample (123641.5 + 621309, 123642.5 + 621256, 123643.1 + 621203, 123646.4 + 621440, 123648.6 + 621123, 123650.2 + 621139, 123655.2 + 621413, 123655.7 + 621427, 123656.1 + 621303, 123656.6 + 621307, 123657.6 + 621205, 123658.6 + 621309 and 123701.2 + 621307); (iii) the complete 15-μm sample (123634.3 + 621238, 123637.5 + 621109, 123646.9 + 621045, 123653.6 + 621140, 123659.4 + 621337 and 123702.5 + 621406); and (iv) the supplementary 15-μm sample (123658.1 + 621458).

A number of these sources have likeliest associations that lie on the sharply falling portion of the curve of $P_{\rm ran}(I_{814})$ against *LR*, and may possibly rise above our reliability threshold once a more accurate model for $e(x,y)$ in equations (1) and (2) can be computed, properly taking into account the as yet uncertain field distortion in ISOCAM data and improving the astrometric accuracy of the *ISO* HDF maps.

4 DISCUSSION AND CONCLUSIONS

We have conservatively associated 15 *ISO* sources detected at 6.7 or 15 μm with optical galaxies in the HDF catalogue of Williams et al. (1996), eight of which are also in the near-infrared catalogue of Songaila (1997): a further association is made with a star. This was done using two independent procedures, namely the likelihood ratio method (Sutherland & Saunders 1992) and visual inspection. These gave consistent results, the reliability of which we tested by computing the likelihood ratios for galaxies to be associated with fictitious sources placed at random in the *Hubble Deep Field*. A similar procedure yielded a further 14 associations with objects (13 galaxies and one star) in the *Hubble Flanking Fields*: more details of this are given in the Appendix.

We detect 10 of the 44 brightest I_{814}-band objects in the Williams et al. (1996) catalogue (i.e. those with $I_{814} < 22.04$): eight of these 44 objects are stars, which we discuss no further. Of the 36 galaxies, we detect 13 per cent (2 out of 15) of the ellipticals, 30 per cent (6/18) of the spirals and 67 per cent (2/3) of the irregulars/mergers. We divide these 36 galaxies into three bins of 12 galaxies each for redshift and the three optical colours, $V_{606} - I_{814}$, $B_{450} - V_{606}$ and $U_{303} - B_{450}$. There are (3, 4, 3) of our galaxies in bins of increasing redshift, so the galaxies associated with the *ISO* HDF sources have a redshift distribution similar to bright HDF galaxies in general: 5 out of 10 have redshifts greater than 0.5. We find (4, 4, 2) of our objects in the bins of increasing $V_{606} - I_{814}$ and of increasing $U_{300} - B_{450}$, and (4, 4, 3) in bins of increasing $B_{450} - V_{606}$. A detailed study of the properties of the galaxies associated with the *ISO* HDF source, contrasting them with those of the HDF galaxy population as a whole, will be the topic of a later paper in this series, but it is clear that, amongst bright HDF galaxies, *ISO* has a tendency to detect luminous, star-forming galaxies at fairly high redshift and with disturbed morphologies, in preference to nearby ellipticals: the implications of this result are discussed in Paper V.

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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APPENDIX A: *FLANKING FIELD* ASSOCIATIONS

In this Appendix we discuss the association of *ISO* HDF sources in the *Hubble Flanking Fields* (HFF) region. We constructed a I_{814}-band catalogue of the HFF using the connected pixel algorithm PISA (Draper & Eaton 1996). No attempt was made to push the detection threshold to include the faintest objects in the HFF images, as we knew that we were principally interested in the brighter galaxies as possible associations for *ISO* sources, on the basis of associations made in the HDF. We used PISA to compute total *AB* magnitudes for the detected objects, which it does using a curve-of-growth estimator. The limiting magnitude of detected objects varied from field to field, and was conservatively set at $I_{814}=24$, which corresponds to the depth of the shallowest field: objects fainter than that were neglected in the association procedure.

The photometric calibration of our HFF catalogue was checked by comparing magnitudes of galaxies in the small overlap between the HDF and HFF, and by comparing magnitudes for those *Flanking Field* galaxies for which the DEEP collaboration (Gallego & Guzman 1997) have measured redshifts. In neither case was there evidence of a systematic offset, apart from a trend for the DEEP magnitudes to be brighter than our PISA magnitudes at the magnitude limit of our catalogue by ~0.2 mag: this has no bearing on the likelihood ratio analysis.

Associations were made with objects in this catalogue using the same likelihood ratio method as described in Section 3. A total of 11 *ISO* HDF sources were reliably associated [using the same reliability criterion as before, i.e. $P_{\rm ran}(I_{814})<0.35$] with objects in the *Flanking Field* catalogue. These are tabulated in Table A1.

Table A1. Properties of the galaxies reliably associated with the *ISO* HDF sources in the *Hubble Flanking Fields*.

ISO Source	RA	Dec	$P_{\rm ran}(I_{814})$	I_{814}	6.7μm	15μm	8.4 GHz	z
J123633.9+621217 3C	12 36 34.4	+62 12 13.9	0.032	18.98	-	726	40.0	-
J123635.9+621134 3C	12 36 36.8	+62 11 35.5	0.005	17.97	-	420	-	0.078
J123636.5+621348 3C	12 36 36.9	+62 13 46.2	0.243	21.63	-	649	-	-
J123639.3+621250 3C	12 36 40.0	+62 12 50.2	0.192	21.18	< 97.57	433	-	
J123653.0+621116 3C	12 36 53.2	+62 11 17.5	0.203	21.47	-	327	-	-
J123657.4+621414 2S	12 36 57.7	+62 14 18.6	0.272	22.25	38.1	< 243	-	-
J123658.7+621212 3C	12 36 59.0	+62 12 09.1	0.267	21.76	< 89.1	336	-	-
J123700.2+621455 3C	12 36 59.8	+62 14 50.5	0.282	21.52	-	291	-	-
J123702.0+621127 3S	12 37 02.0	+62 11 23.0	0.032	18.92	-	326	-	0.136
J123705.7+621157 3C	12 37 05.9	+62 11 53.8	0.161	20.96	-	472	-	0.904

The first column gives the *ISO* source name, as listed in Paper II, minus 'ISOHDF' and the prefix indicating in which band the source was detected. This latter information is indicated by '2' (LW2 filter, 6.7 μm) and '3' (LW3 filter, 15 μm) following the source name: 'C' or 'S' indicates whether the *ISO* source comes from the complete or supplementary sample for that waveband. The next columns give the RA and Dec. of the associated galaxy, in J2000 coordinates, followed by the value of $P_{\rm ran}(I_{814})$ for the association, and the I_{814} total magnitude of the associated object. Following that are the source fluxes in the two *ISO* bands (in μJy), after which is the 8.4-GHz radio flux from Fomalont et al. (1997) also in μJy. The final column lists the spectroscopic redshifts of the three galaxies for which they have been measured: those for ISOHDF3C J123702.0 + 621127 and ISOHDF3C J123705.7 + 621157 come from Phillips et al. (1997), while that for ISOHDF3C J123635.9 + 621134 is from Moustakas, Zepf & Davis (1997). One reliable association is omitted from this table: ISOHDF3C J123709.8 + 621239 is associated with a star.