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


1Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2BZ
2Service d’Astrophysique, Saclay, 91191, Gif-sur-Yvette Cedex, France
3SISSA, Via Beirut 2-4, Trieste, Italy
4Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122, Padova, Italy
5Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D-8046, Garching bei München, Germany
6Astronomical Institute, National Observatory of Athens, PO Box 200048, GR-118 10, Athens, Greece
7Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ
8Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA
9Danish Space Research Institute, Gåselundvej 7, DK-2800 Lyngby, Copenhagen, Denmark
10Instituto de Astrofisica de Canarias, Via Lactea, E-38200 La Laguna, Tenerife, Canary Islands, Spain
11Instituto de Fisica de Cantabria, Santander, Spain

Accepted 1997 May 9. Received 1997 March 24; in original form 1996 December 5

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 [I814(AB) < 23] galaxies in the HDF, and one with an I814(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_{6.7} < 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_{250}, 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, and feel that it is unlikely to affect our results significantly. Another issue is the band in which to make the associations, and feel that it is unlikely to affect our results significantly. Another issue is the band in which to make the associations, and feel that it is unlikely to affect our results significantly. Another issue is the band in which to make the associations, and feel that it is unlikely to affect our results significantly. Another issue is the band in which to make the associations, and feel that it is unlikely to affect our results significantly.

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_{true} = 1.6 × 10^{-3} that the two magnitude distributions are drawn from the same population (falling to P_{true} = 5.4 × 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.

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_{true}, of finding the true counterpart to the source at the position of the object and with its flux, to the probability, P_{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

$$p_{\text{true}} = q(f)\,e(x, y)\,df\,dx\,dy,$$

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 $p_{\text{true}} = n(f)\,df\,dx\,dy$ and $LR$ is given by

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

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 $\sigma$-value equal to the quadrature sum of the radius of the Airy disc for the ISOCAM sources (2.8 arcsec at 6.7 $\mu$m and 6.0 arcsec at 15 $\mu$m) 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 & Sanders (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 $\mu$m 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-$\mu$m 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 $P_{\text{ran}}(L_{R\text{ran}})$, which is the probability that a fictitious source, placed at random in the HDF, would have a likelihood 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 $P_{\text{ran}}$ value for the best optical candidates for the 6.7-$\mu$m sources marking the boundary above which the observers conservatively considered their associations to be reliable was about $P_{\text{ran}} = 0.35$. 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.

![Figure 2](http://mnras.oxfordjournals.org/)

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

© 1997 RAS, MNRAS 289, 482–489

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System
Table 1. Properties of the galaxies reliably associated with the ISO HDF sources in the Hubble Deep Field.

<table>
<thead>
<tr>
<th>ISO Source</th>
<th>ST</th>
<th>RA</th>
<th>Dec</th>
<th>$P_{\text{tot}}(I_{1814})$</th>
<th>$U_{300}$</th>
<th>$B_{450}$</th>
<th>$V_{606}$</th>
<th>$I_{114}$</th>
<th>HA</th>
<th>$H + K$</th>
<th>$6.7\mu$m</th>
<th>$15\mu$m</th>
<th>8.4 GHz</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>J123641.1+621129 3C</td>
<td>4.986.0</td>
<td>41.64</td>
<td>61.31</td>
<td>0.031</td>
<td>21.23</td>
<td>20.33</td>
<td>19.96</td>
<td>19.71</td>
<td>-</td>
<td>-</td>
<td>&lt; 89.6</td>
<td>376</td>
<td>-</td>
<td>(0.047)</td>
</tr>
<tr>
<td>J123641.6+621142 2S</td>
<td>4.986.0</td>
<td>41.31</td>
<td>61.40</td>
<td>0.083</td>
<td>24.96</td>
<td>23.76</td>
<td>23.00</td>
<td>22.04</td>
<td>-</td>
<td>-</td>
<td>51.6</td>
<td>265</td>
<td>-</td>
<td>0.585</td>
</tr>
<tr>
<td>J123642.6+621210 2S</td>
<td>4.986.0</td>
<td>42.91</td>
<td>62.16</td>
<td>0.322</td>
<td>22.81</td>
<td>22.17</td>
<td>21.27</td>
<td>20.70</td>
<td>11</td>
<td>20.15</td>
<td>20.22</td>
<td>22.9</td>
<td>&lt; 287</td>
<td>-</td>
</tr>
<tr>
<td>J123642.9+621306 2S</td>
<td>1.570</td>
<td>42.72</td>
<td>63.07</td>
<td>0.061</td>
<td>24.64</td>
<td>23.94</td>
<td>22.91</td>
<td>21.94</td>
<td>-</td>
<td>-</td>
<td>51.1</td>
<td>170</td>
<td>-</td>
<td>(0.737)</td>
</tr>
<tr>
<td>J123643.0+621153 2S</td>
<td>4.775.0</td>
<td>43.18</td>
<td>61.48</td>
<td>0.407</td>
<td>25.94</td>
<td>24.85</td>
<td>23.87</td>
<td>22.45</td>
<td>20</td>
<td>20.90</td>
<td>20.67</td>
<td>57.9</td>
<td>&lt; 336</td>
<td>-</td>
</tr>
<tr>
<td>J123643.7+621255 3C</td>
<td>4.986.0</td>
<td>44.19</td>
<td>62.47</td>
<td>0.199</td>
<td>22.48</td>
<td>21.90</td>
<td>21.13</td>
<td>20.45</td>
<td>32</td>
<td>19.90</td>
<td>19.87</td>
<td>&lt; 43.2</td>
<td>319</td>
<td>13.0</td>
</tr>
<tr>
<td>J123643.5+621330 2C</td>
<td>4.752.0</td>
<td>44.35</td>
<td>61.90</td>
<td>0.203</td>
<td>25.51</td>
<td>25.32</td>
<td>23.08</td>
<td>21.31</td>
<td>-</td>
<td>-</td>
<td>50.4</td>
<td>&lt; 225</td>
<td>458.0</td>
<td>1.013</td>
</tr>
<tr>
<td>J123646.4+621406 2S</td>
<td>2.251.0</td>
<td>46.34</td>
<td>64.04</td>
<td>0.395</td>
<td>35.29</td>
<td>33.64</td>
<td>22.49</td>
<td>21.32</td>
<td>9</td>
<td>20.07</td>
<td>20.04</td>
<td>52.1</td>
<td>&lt; 381</td>
<td>152.0</td>
</tr>
<tr>
<td>J123648.1+621432 2C</td>
<td>2.537.0</td>
<td>48.32</td>
<td>64.26</td>
<td>0.031</td>
<td>21.11</td>
<td>20.09</td>
<td>19.49</td>
<td>18.19</td>
<td>-</td>
<td>-</td>
<td>49.8</td>
<td>231</td>
<td>-</td>
<td>(0.023)</td>
</tr>
<tr>
<td>J123648.4+621427 2C</td>
<td>2.537.0</td>
<td>48.33</td>
<td>64.26</td>
<td>0.002</td>
<td>21.11</td>
<td>20.09</td>
<td>19.49</td>
<td>18.19</td>
<td>-</td>
<td>-</td>
<td>65.7</td>
<td>&lt; 243</td>
<td>-</td>
<td>(0.023)</td>
</tr>
<tr>
<td>J123648.4+621215 2S</td>
<td>4.260.111</td>
<td>48.24</td>
<td>62.12</td>
<td>0.207</td>
<td>24.16</td>
<td>23.84</td>
<td>23.52</td>
<td>22.67</td>
<td>45</td>
<td>21.82</td>
<td>21.79</td>
<td>51.2</td>
<td>&lt; 295</td>
<td>-</td>
</tr>
<tr>
<td>J123649.7+621315 2C</td>
<td>2.264.1</td>
<td>49.76</td>
<td>63.13</td>
<td>0.080</td>
<td>24.92</td>
<td>23.48</td>
<td>22.24</td>
<td>21.46</td>
<td>17</td>
<td>20.61</td>
<td>20.28</td>
<td>48.1</td>
<td>440</td>
<td>22.0</td>
</tr>
<tr>
<td>J123649.8+621319 3C</td>
<td>2.264.1</td>
<td>49.76</td>
<td>63.13</td>
<td>0.337</td>
<td>24.92</td>
<td>23.38</td>
<td>22.24</td>
<td>21.46</td>
<td>17</td>
<td>20.61</td>
<td>20.28</td>
<td>52.3</td>
<td>472</td>
<td>22.0</td>
</tr>
<tr>
<td>J123651.5+621357 3S</td>
<td>2.652.0</td>
<td>51.78</td>
<td>63.53</td>
<td>0.063</td>
<td>23.96</td>
<td>22.96</td>
<td>21.94</td>
<td>21.08</td>
<td>10</td>
<td>20.23</td>
<td>20.00</td>
<td>51.4</td>
<td>155</td>
<td>-</td>
</tr>
<tr>
<td>J123658.9+621248 2S</td>
<td>3.534.0</td>
<td>58.76</td>
<td>62.52</td>
<td>0.262</td>
<td>22.99</td>
<td>22.35</td>
<td>21.58</td>
<td>21.18</td>
<td>27</td>
<td>20.63</td>
<td>20.60</td>
<td>43.1</td>
<td>&lt; 279</td>
<td>-</td>
</tr>
</tbody>
</table>

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 12h36m and +62° subtracted from the RA and Dec, respectively. The fifth column gives the value of $P_{\text{tot}}(I_{1814})$ for the association. The next four columns give the total magnitudes of the associated galaxy in the $U_{300}, B_{450}, V_{606}$ and $I_{114}$ 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 $V_{606} - I_{114}$ colours. The column headed 'HA' gives the entry number of the associated galaxy in the Songaila (1997) catalogue, which is followed by the total $J + H + K$ magnitudes for the galaxy, computed from the aperture magnitudes given by Songaila (1997), using the $I_{114}$ magnitudes 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 $2\sigma$ 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-\mu m complete samples are at least 71 and 68 per cent reliable, respectively, while the reliabilities of the supplementary 6.7- and 15-\mu m 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 $I_{60}$ HDF image are denoted by the names assigned by Williams et al., 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 'IF', and photometric redshifts have been computed using the method of Mobasher et al. (1996), without using the ISO data themselves.

(i) ISOHDF J123641.1 + 621129. The position of this 15-\mu m source falls just inside the HDF, 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) ISOHDF 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) ISOHDF J123642.6 + 621210. This source falls mid-way between two spiral galaxies: ST4-656.0/IFIA1, which is 0.454: Songaila (1997) and ST4-795.0/IFIA14 ($z=0.432$: 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) ISOHDF 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) ISOHDF J123643.0 + 621152. This source may have flux contributed by ST4-727.0/IFIA9, as well as ST4-775.0/IFIA20, as listed in Table 1. ST4-727.0/IFIA9 is half a magnitude fainter in $I_{60}$ than ST4-775.0/IFIA20, but is closer to the ISO position, and so yields a lower value of $P_{ISO}(I_{60})$: $P_{ISO}(I_{60})=0.269$ against $P_{ISO}(I_{60})=0.407$ for ST4-775.0/IFIA20. Despite that, we conservatively take ST4-775.0/IFIA20 as the association, on the basis of its lower photometric redshift: $z=0.820$, versus $z=1.63$ for ST4-727.0/IFIA9. Having two galaxies with such low $P_{ISO}(I_{60})$ 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 $P_{ISO}(I_{60})<0.35$ in this one case.

(vii) ISOHDF J123643.7 + 621255. This is associated with the brighter member (ST4-402.0/IFIA23) of an interacting pair of galaxies on the basis of extremely reliable $I_{60}$ data: $P_{ISO}(I_{60})=0.025$. Cohen et al. (1996) give a spectroscopic redshift of $z=0.538$ for this galaxy.

(vi) ISOHDF J123643.9 + 621130. ST4-752.0 has an acceptable $P_{ISO}(I_{60})$ 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).

(xii) ISOHDF J123648.2 + 621247. This is identified as a stellar object (ST2-381.0). The $V_{60},I_{60},J+K$ magnitudes can be fitted very well with a $T=3450$ K blackbody, so this appears to be a M0 star. The corresponding predicted flux at 6.7 \mu m would be 15 \mu Jy, 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).

(xiii) ISOHDF J123649.7 + 621315. This 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).

(xiv) ISOHDF J123649.8 + 621319. This source lies in the same group of galaxies as ISOHDF J123649.7 + 621315 and, as with that source, we favour ST2-264.1/IFIA17 as the most likely association, but note that it is likely that this 15-\mu m source includes flux from ST2-256.0/IFIA43 and ST2-239.0/IFIA35. ST2-264.1/IFIA17 has a spectroscopic redshift of $z=0.475$ (Cohen et al. 1996).
Figure 3. Positions of ISO HDF sources and their associations, from a $I_{160}$-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.
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 + 621213, 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 likely associations that lie on the sharply falling portion of the curve of $P_{\text{rel}}(I_{\text{tot}})$ 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 $I_{606}$-band objects in the Williams et al. (1996) catalogue (i.e. those with $I_{606} < 22.04$): 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, $V_{606} - I_{606}$, $B_{450} - V_{606}$ and $U_{300} - B_{450}$. 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 $V_{606} - I_{606}$ 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://arternis.ph.ic.ac.uk/hdf/).

ACKNOWLEDGMENTS

This paper is based on observations with ISO, an ESA project with instruments funded by ESA member states (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA. This work was supported by PPARC grant GR/K98728 and by the EC TMR Network FMRX-CT96-0068. We thank the referee, Harry Ferguson, for many helpful comments.

REFERENCES

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 $\sim 0.2$ 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. $P_{\text{ran}}(I_{814}) < 0.35$] with objects in the Flanking Field catalogue. These are tabulated in Table A1.

<table>
<thead>
<tr>
<th>ISO Source</th>
<th>RA</th>
<th>Dec</th>
<th>$P_{\text{ran}}(I_{814})$</th>
<th>$I_{814}$</th>
<th>6.7 $\mu$m</th>
<th>15 $\mu$m</th>
<th>8.4 GHz</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>J123633.9+621217 3C</td>
<td>12 36 34.4</td>
<td>+62 12 13.9</td>
<td>0.032</td>
<td>18.98</td>
<td>-</td>
<td>726</td>
<td>40.0</td>
<td>-</td>
</tr>
<tr>
<td>J123635.9+621134 3C</td>
<td>12 36 36.8</td>
<td>+62 11 35.5</td>
<td>0.005</td>
<td>17.97</td>
<td>-</td>
<td>420</td>
<td>-</td>
<td>0.078</td>
</tr>
<tr>
<td>J123636.5+621348 3C</td>
<td>12 36 36.9</td>
<td>+62 13 46.2</td>
<td>0.243</td>
<td>21.63</td>
<td>-</td>
<td>649</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J123639.3+621250 3C</td>
<td>12 36 40.0</td>
<td>+62 12 50.2</td>
<td>0.192</td>
<td>21.18</td>
<td>&lt; 97.57</td>
<td>433</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J123653.0+621116 3C</td>
<td>12 36 53.2</td>
<td>+62 11 17.5</td>
<td>0.203</td>
<td>21.47</td>
<td>-</td>
<td>327</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J123657.4+621414 2S</td>
<td>12 36 57.7</td>
<td>+62 14 18.6</td>
<td>0.272</td>
<td>22.25</td>
<td>38.1</td>
<td>&lt; 243</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J123658.7+621212 3C</td>
<td>12 36 59.0</td>
<td>+62 12 09.1</td>
<td>0.267</td>
<td>21.76</td>
<td>&lt; 89.1</td>
<td>336</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J123700.2+621455 3C</td>
<td>12 36 59.8</td>
<td>+62 14 50.5</td>
<td>0.282</td>
<td>21.52</td>
<td>-</td>
<td>241</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J123702.0+621127 3S</td>
<td>12 37 02.0</td>
<td>+62 11 23.0</td>
<td>0.032</td>
<td>18.92</td>
<td>-</td>
<td>326</td>
<td>-</td>
<td>0.136</td>
</tr>
<tr>
<td>J123705.7+621157 3C</td>
<td>12 37 05.9</td>
<td>+62 11 53.8</td>
<td>0.161</td>
<td>20.96</td>
<td>-</td>
<td>472</td>
<td>-</td>
<td>0.904</td>
</tr>
</tbody>
</table>

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 $\mu$m) and '3' (LW3 filter, 15 $\mu$m) 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 $P_{\text{ran}}(I_{814})$ 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 $\mu$Jy), after which is the 8.4-GHz radio flux from Fomalont et al. (1997) also in $\mu$Jy. 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.