Near- and mid-infrared colours of star-forming galaxies in European Large Area ISO Survey fields

Article  (Published Version)


This version is available from Sussex Research Online: http://sro.sussex.ac.uk/id/eprint/29655/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher’s version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.
Near- and mid-infrared colours of star-forming galaxies in European Large Area ISO Survey fields

P. Väisänen,1,2 T. Morel,3,4,5 M. Rowan-Robinson,3 S. Serjeant,3 S. Oliver,3,6 T. Sumner,3 H. Crockett,3 C. Gruppioni7,8 and E. V. Tollestrup9,10

1 Observatory, PO Box 14, University of Helsinki, Finland
2 European Southern Observatory, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
3 Astrophysics Group, Blackett Laboratory, Imperial College of Science, Technology & Medicine, Prince Consort Road, London SW7 2BZ
4 IUCAA, Post Bag 4, Ganeshkhind, Pune 411 007, India
5 Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy
6 Astronomy Centre, Physics and Astronomy Subject Group, School of CPES, University of Sussex, Falmer, Brighton BN1 9QJ
7 Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, 35122 Padova, Italy
8 Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
9 Boston University, Department of Astronomy, 725 Commonwealth Avenue, Boston, MA 02215, USA
10 Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Accepted 2002 August 16. Received 2002 February 4; in original form 2001 May 30

ABSTRACT
We present J- and K-band near-infrared (near-IR) photometry of a sample of mid-infrared (mid-IR) sources detected by the Infrared Space Observatory (ISO) as part of the European Large Area ISO Survey (ELAIS) and study their classification and star-forming properties. We have used the Preliminary ELAIS Catalogue for the 6.7-µm (LW2) and 15-µm (LW3) fluxes. All of the high-reliability LW2 sources and 80 per cent of the LW3 sources are identified in the near-IR survey reaching K ≈ 17.5 mag. The near-IR/mid-IR flux ratios can effectively be used to separate stars from galaxies in mid-IR surveys. The stars detected in our survey region are used to derive a new accurate calibration for the ELAIS ISOCAM data in both the LW2 and LW3 filters. We show that near- to mid-IR colour–colour diagrams can be used to classify galaxies further, as well as to study star formation. The ELAIS ISOCAM survey is found mostly to detect strongly star-forming late-type galaxies, possibly starburst-powered galaxies, and it also picks out obscured active galactic nuclei. The ELAIS galaxies yield an average mid-IR flux ratio LW2/LW3 = 0.67 ± 0.27. We discuss the f_c(6.7 µm)/f_c(15 µm) ratio as a star formation tracer using ISO and IRAS data of a local comparison sample. We find that the f_c(2.2 µm)/f_c(15 µm) ratio is also a good indicator of activity level in galaxies and conclude that the drop in the f_c(6.7 µm)/f_c(15 µm) ratio seen in strongly star-forming galaxies is a result of both an increase of 15-µm emission and an apparent depletion of 6.7-µm emission. Near-IR together with the mid-IR data make it possible to estimate the relative amount of interstellar matter in the galaxies.

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

1 INTRODUCTION
There has been determined effort over the past several years to understand the history of luminous matter in the Universe. Ultimately, one wishes to have a consistent understanding that would tie together the detailed physical processes at work in stars and interstellar medium (ISM) in the Milky Way and local galaxies with the integrated properties of more distant systems. The spectral properties and energy budget of the distant galaxies in turn are crucial in understanding the universal history of star formation, the very faintest source counts and the extragalactic background radiation.

In particular, the infrared (IR) and submillimetre regimes have become the focal point of interest in studies of galaxies, both normal and extreme objects. The near-infrared (near-IR) is an important region for galaxy evolution studies for several reasons. Dust extinction is significantly less hampering here than in the optical, and the light mostly comes from a relatively stable old population of...
late-type stars, making galaxy colours, counts and k-corrections easier to predict and interpret. It is also in the near-IR that the energy output of a galaxy starts to shift from normal starlight to emission re-radiated by the ISM. By 5 μm, the dust emission has taken over from radiation from stellar photospheres, except in most ellipticals.

Apart from the [12/25] ≈ f_1(12 μm)/f_2(25 μm) colours of IRAS galaxies, the mid-infrared (mid-IR) truly opened up for study only with the ISO mission (see reviews by Genzel & Cesarsky 2000; Helou 1999). Many studies (e.g. Mattila, Lehtinen & Lemke 1999; Helou et al. 2000) have confirmed the complex nature of the spectral energy distributions (SEDs) of disc galaxies in the 3–20 μm range.

In addition to a continuum due to hot (or warm) dust, there are bright IR bands at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 μm – these are often called the unidentified infrared bands (UIBs), because of the lack of understanding of their carriers. These broad-band aromatic features are proposed to be the signature of polycyclic aromatic hydrocarbons (PAHs; Léger & Puget 1984).

The PAHs is an essential component in forming the mid-IR [6.7/15] colour ratio, which is emerging as a tracer of star-forming activity in galaxies (Sauvage et al. 1996; Vigroux et al. 1996, 1999; Dale et al. 2000; Helou 2000; Roussel et al. 2001a). The value [6.7/15] ≈ 1 is expected in quiescent medium and photodissociation regions (PDRs), while H II regions have [6.7/15] < 0.5 (e.g. Cesarsky et al. 1996). The [6.7/15] ratio thus remains close to unity for quiescent and mildly star-forming galaxies, while it starts to drop for those with more vigorous star formation activity. This mid-IR flux ratio has also been shown to correlate with the IRAS [60/100] colour ratio, which is a well-known indicator of activity level in galaxies (Vigroux et al. 1999; Helou 2000; Dale et al. 2000). A two-component model of a galaxy as a linear combination of differing amounts of cold dust in cirrus clouds and warmer dust in H II regions has been seen as the explanation for the IRAS and IRAS/ISO colour–colour diagrams (Helou 1986; Dale et al. 1999, 2000). On the other hand, the situation might be more complicated (see e.g. Sauvage & Thuan 1994), and for example it is possible that the proportion of star formation in the disc relative to the central region of a galaxy plays a dominant role (e.g. Vigroux et al. 1999; Roussel et al. 2001b).

On another front, deep ISO galaxy counts (e.g. Oliver et al. 1997; Taniguchi et al. 1997; Elbaz et al. 1999a; Aussel et al. 1999; Flores et al. 1999, for ISOCAM counts) have produced surprising results. The differential 15–20 μm fluxes become available without high-resolution data, and the various corrections are expected to be helpful in the future, e.g. with SIRTF and ASTRO-F data, when large numbers of galaxies with near- and mid-IR fluxes become available without high-resolution spectra accompanying them at least in the first instance. In Section 4.2 we discuss star formation properties of the ELAIS galaxies, and the mid-IR and near- to mid-IR colours as tracers of star formation. Finally, active galaxies and extreme objects are discussed in Section 4.3.

## 2 OBSERVATIONS AND DATA

### 2.1 ISO data

The mid-IR ELAIS ISO observations were made with the ISOCAM LW2 (6.7 μm) and LW3 (15 μm) filters, covering ranges 5–8.5 μm and 12–18 μm, respectively. For a description of the observations, data reduction and source extraction, we refer the reader to Oliver et al. (2000) and Serjeant et al. (2000). At present the final reduction products are available only for the ELAIS southern fields (Lari et al. 2001), and thus we use here the preliminary analysis v.1.3 ELAIS ISOCAM catalogue source list. This is somewhat deeper than the publicly available v.1.4 catalogue but otherwise equivalent (the latter is a subset of v.1.3). At this stage the detections are classified as ‘secure’ (REL = 2) or ‘likely’ (REL = 3). However, to have a reliable source list, we will consider only those detections with near-IR matches, as discussed below. The reliability and completeness of these ELAIS ISO catalogues will be discussed in more detail in Babbedge & Rowan-Robinson (in preparation). Part of our near-IR survey is in the ELAIS N1 region, which was not observed at 6.7 μm.

### 2.2 Near-infrared data

The near-IR observations were carried out using the STELIRCam instrument at the 1.2-m telescope of the F. L. Whipple Observatory on Mount Hopkins. A description of these J- and K-band data (taken during 21 nights between 1997 April and 1999 May), reduction as well as photometry can be found in Väisänen et al. (2000). The survey area is approximately 1 deg², two-thirds of which is in the ELAIS N2 region (centred at RA 16 h 36min 00s, Dec. 41 deg 06min 00s) and the rest in N1 (RA 16 h 09min 00s, Dec. 54 deg 40min 00s). There is a small offset between the simultaneously observed fields of view (FOVs) in the J and K bands, resulting in slightly different source catalogues in the respective bands.

The 2MASS second incremental data release (Cutri et al. 2000) partially covers the N1 and N2 regions. This allows us to cross-check our bright (K < 14.5) photometry directly with 2MASS. This is important also because we will later use 2MASS data in connection with a comparison sample of nearby galaxies from the literature. The ‘default’ photometry of 2MASS was found to agree very well with our photometry for both stars and galaxies. Our data from Mount Hopkins (while deeper as a result of the longer integration time) are, in fact, taken with a very similar telescope and instrument to the 2MASS data.

---

1 Available at http://athena.ph.ic.ac.uk/elais/data.html

with data from both ISOCAM bands and near-IR photometry also discuss them further here, except to note that eight of our 29 galaxies discussed in another work (Morel et al., in preparation), we do not.

Since in this work we need to compare fluxes between nearby and distant galaxies, total fluxes are required for both the near- and mid-IR. In Väisänen et al. (2000) we found the ‘BEST’ magnitudes from SExtractor (Bertin & Arnouts 1996) to be the most robust and accurate over a wide range of magnitudes and source profiles. The Kron-type ‘BEST’ magnitudes are presented in Table 2, but we calculated also various aperture magnitudes and there is no difference in any final results if large enough apertures are used.

The ISO fluxes are measured from characteristic temporal signatures of individual pixels, as described in Serjeant et al. (2000). Instead of conventional aperture photometry, the value of the peak pixel is corrected to total flux using point spread function (PSF) modelling. The adopted correction factors were 1.54 at 6.7 µm and 2.36 at 15 µm. The correction for the LW2 filter is more uncertain because of the much undersampled PSF. Strictly, this correction is appropriate for point sources only, which results in a potentially serious underestimation of fluxes for extended objects. However, the size of the ISOCAM pixel is 6 arcsec, and the large majority of our sources are smaller than this, and we trust that the point source aperture correction gives an accurate value for them. Nevertheless, we examined the largest ELAIS galaxies individually (using their near-IR half-light radii and testing with different apertures) to get an estimate of correction factors to the mid-IR fluxes. We conclude that only four of the galaxies, all of which are included in Fig. 1, definitely need a significant aperture correction. For the largest galaxy in our sample (ELAISC15 J163508+405933), referred to as ‘B’ in Table 2 and Fig. 1, we adopt fluxes from Morel et al. (in preparation), modified in accordance with our new calibration (Section 2.6). The correction is very large, approximately a factor of 4. The other three galaxies labelled ‘A’, ‘C’ and ‘D’, respectively, are significantly smaller, and for these we adopt an approximate correction factor of 1.5.

### 2.3 Matching of mid- and near-infrared data

The ELAIS ISOCAM catalogue has 1322 and 2203 sources in total for all ELAIS regions in the 6.7 and 15 µm bands, respectively. These were matched with our near-IR catalogue, which comes from a much smaller area. The ELAIS v.1.3 catalogue includes many double, or even multiple, detections from the edges of neighbouring individual rasters and repeated observations – thus we had to purge the catalogue. We searched for ISOCAM objects separated initially by 1 arcsec, then 3 arcsec and finally 6 arcsec – at each step neighbours were merged if they had the same near-IR counterpart. Ultimately, the matched and purged catalogue consists of 217 and 158 near-IR sources matched with the LW2 and LW3 ELAIS catalogue, respectively. Of these, 53 are common to both ISOCAM filters, and because of LW2 coverage they are all in the N2 region.

<table>
<thead>
<tr>
<th></th>
<th>Detections</th>
<th>Identified</th>
<th>Stars</th>
<th>Galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>LW3</td>
<td>REL = 2</td>
<td>47</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>REL = 3</td>
<td>59</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>N2</td>
<td>LW2</td>
<td>REL = 2</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>REL = 3</td>
<td>53</td>
<td>47</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>LW3</td>
<td>REL = 2</td>
<td>68</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>REL = 3</td>
<td>115</td>
<td>49</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>LW2 &amp; LW3</td>
<td>REL = 2 &amp; 3</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td></td>
<td>223</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td>LW2</td>
<td></td>
<td>289</td>
<td>158</td>
</tr>
</tbody>
</table>

### 2.4 Photometry

Since in this work we need to compare fluxes between nearby and distant galaxies, total fluxes are required for both the near- and mid-IR.
of the 6.7-μm sources are stars; at 15 μm only 21 per cent of the objects are stars.

2.6 Flux calibration of ELAIS ISOCAM data using stars

Before removing the stars from further consideration in this paper, we use them for an accurate flux calibration of the ELAIS ISO data. We matched observed near- and mid-IR colours to corresponding model colours of IR standard stars, and are able to derive the flux calibration for the ELAIS ISOCAM data with better accuracy than done previously. The derivation is performed in Appendix A: we adopt values of 1.23 and 1.05 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\) for the LW2 and LW3 filters, respectively, i.e. the catalogue v.1.3 values for LW2 and LW3 have to be multiplied by these factors to have fluxes in millijansky. Note that the factors were not included in Figs 2 and 3. [The LW3 calibration is in disagreement with the one performed in Serjeant et al. (2000), where a value of 1.75 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\) was found.] Our values are in good agreement with the ISOCAM handbook values of 2.32 and 1.96 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\) (Blommaert 1998), where an additional factor of 2 correction for signal stabilization has been included (see Appendix A for details). This lends strong support for the accuracy of the reduction and photometric techniques used in the creation of the ELAIS preliminary catalogue. Furthermore, we can use the bright stars to estimate the completeness of the ELAIS ISOCAM catalogue. Using the mean mid-IR/near-IR flux ratio for stars (see Appendix A and also Figs 2 and 3), we calculate the expected mid-IR fluxes of all bright near-IR stars in our field, and then check whether they actually are included in the ELAIS catalogue. The results are as follows: The 15-μm catalogue is essentially complete above 2 mJy. Below this the completeness begins to drop rapidly. Six stars out of 20 between 1.0 and 2.0 mJy are detected. The 6.7-μm band is essentially complete above 1.5 mJy. The completeness above 1 mJy is 80 per cent, while only 18 out of 73 stars between 0.5 and 1.0 mJy are detected. These numbers are consistent with those derived by Serjeant et al. (2000), who find the 50 per cent completeness limits for the whole ELAIS survey to be ∼1 mJy for both bands (using the calibration of this paper for the 15-μm data).

### Table 2. The near-IR sample of ELAIS galaxies detected with both ISOCAM filters. The galaxies are ordered with decreasing 15-μm flux. Columns 7 and 9 labelled ‘R’ refer to the REL parameter. The coordinates (J2000) are from the near-IR data. The bright galaxies A to E from Fig. 1 are indicated; ‘fir’ and ‘vla’ indicate that the object has been detected in the 90-μm ELAIS survey (Efstathiou et al. 2000) and a VLA follow-up survey (Ciliegi et al. 1999); ‘q1’ and ‘q2’ indicate a confirmed and potential quasar, respectively, as discussed in Section 4.3.

<table>
<thead>
<tr>
<th>RA</th>
<th>Dec.</th>
<th>J (mag)</th>
<th>J error</th>
<th>K (mag)</th>
<th>K error</th>
<th>(S_{15}) (mJy)</th>
<th>R</th>
<th>(S_{24}) (mJy)</th>
<th>R</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>37.34</td>
<td>+0.52</td>
<td>0.08</td>
<td>13.23</td>
<td>0.02</td>
<td>34.3</td>
<td>2</td>
<td>37.3</td>
<td>C, vla</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>34.01</td>
<td>+0.18</td>
<td>0.04</td>
<td>12.01</td>
<td>0.03</td>
<td>23.5</td>
<td>2</td>
<td>22.2</td>
<td>'B', 'r', vla</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>37.29</td>
<td>+0.44</td>
<td>0.07</td>
<td>12.35</td>
<td>0.04</td>
<td>18.5</td>
<td>2</td>
<td>11.8</td>
<td>'E', r, vla</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>35.25</td>
<td>+0.54</td>
<td>0.08</td>
<td>12.99</td>
<td>0.03</td>
<td>8.8</td>
<td>2</td>
<td>9.0</td>
<td>'v', r, vla</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>37.05</td>
<td>+0.30</td>
<td>0.05</td>
<td>15.26</td>
<td>0.05</td>
<td>14.0</td>
<td>2</td>
<td>3.8</td>
<td>'r', vla</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>35.59</td>
<td>+0.34</td>
<td>0.07</td>
<td>14.80</td>
<td>0.05</td>
<td>13.5</td>
<td>2</td>
<td>5.3</td>
<td>'v'</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
<td>36.08</td>
<td>+0.34</td>
<td>0.07</td>
<td>15.51</td>
<td>0.03</td>
<td>13.8</td>
<td>2</td>
<td>2.7</td>
<td>'v'</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>35.06</td>
<td>+0.30</td>
<td>0.04</td>
<td>15.48</td>
<td>0.04</td>
<td>14.1</td>
<td>2</td>
<td>4.9</td>
<td>'r', 'v'</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>35.46</td>
<td>+0.32</td>
<td>0.06</td>
<td>15.35</td>
<td>0.04</td>
<td>5.6</td>
<td>2</td>
<td>3.0</td>
<td>'v'</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>36.45</td>
<td>+0.32</td>
<td>0.06</td>
<td>14.23</td>
<td>0.04</td>
<td>13.5</td>
<td>2</td>
<td>1.7</td>
<td>'r'</td>
</tr>
<tr>
<td>11</td>
<td>16</td>
<td>36.13</td>
<td>+0.32</td>
<td>0.06</td>
<td>12.43</td>
<td>0.02</td>
<td>12.4</td>
<td>2</td>
<td>3.1</td>
<td>'v'</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>36.07</td>
<td>+0.32</td>
<td>0.06</td>
<td>15.83</td>
<td>0.05</td>
<td>14.3</td>
<td>2</td>
<td>1.3</td>
<td>'r', 'v', vla</td>
</tr>
<tr>
<td>13</td>
<td>16</td>
<td>37.08</td>
<td>+0.33</td>
<td>0.06</td>
<td>15.26</td>
<td>0.04</td>
<td>13.9</td>
<td>2</td>
<td>2.1</td>
<td>'v'</td>
</tr>
<tr>
<td>14</td>
<td>16</td>
<td>37.31</td>
<td>+0.33</td>
<td>0.06</td>
<td>15.47</td>
<td>0.04</td>
<td>14.1</td>
<td>2</td>
<td>3.7</td>
<td>'r', vla</td>
</tr>
<tr>
<td>15</td>
<td>16</td>
<td>36.14</td>
<td>+0.33</td>
<td>0.06</td>
<td>14.79</td>
<td>0.03</td>
<td>13.9</td>
<td>2</td>
<td>1.5</td>
<td>'v'</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>36.12</td>
<td>+0.33</td>
<td>0.06</td>
<td>17.59</td>
<td>0.11</td>
<td>15.4</td>
<td>2</td>
<td>1.4</td>
<td>'v'</td>
</tr>
<tr>
<td>17</td>
<td>16</td>
<td>37.20</td>
<td>+0.33</td>
<td>0.06</td>
<td>12.92</td>
<td>0.01</td>
<td>11.6</td>
<td>2</td>
<td>2.7</td>
<td>'v'</td>
</tr>
<tr>
<td>18</td>
<td>16</td>
<td>36.09</td>
<td>+0.33</td>
<td>0.06</td>
<td>15.89</td>
<td>0.05</td>
<td>14.4</td>
<td>2</td>
<td>2.1</td>
<td>'v'</td>
</tr>
<tr>
<td>19</td>
<td>16</td>
<td>35.19</td>
<td>+0.33</td>
<td>0.06</td>
<td>16.27</td>
<td>0.07</td>
<td>14.9</td>
<td>2</td>
<td>2.7</td>
<td>'v'</td>
</tr>
<tr>
<td>20</td>
<td>16</td>
<td>38.51</td>
<td>+0.33</td>
<td>0.06</td>
<td>15.80</td>
<td>0.08</td>
<td>14.2</td>
<td>2</td>
<td>2.7</td>
<td>'v'</td>
</tr>
<tr>
<td>21</td>
<td>16</td>
<td>34.23</td>
<td>+0.33</td>
<td>0.06</td>
<td>15.94</td>
<td>0.06</td>
<td>14.2</td>
<td>2</td>
<td>1.6</td>
<td>'v'</td>
</tr>
<tr>
<td>22</td>
<td>16</td>
<td>37.16</td>
<td>+0.33</td>
<td>0.06</td>
<td>14.99</td>
<td>0.03</td>
<td>13.9</td>
<td>2</td>
<td>2.1</td>
<td>'v'</td>
</tr>
<tr>
<td>23</td>
<td>16</td>
<td>35.34</td>
<td>+0.33</td>
<td>0.06</td>
<td>18.02</td>
<td>0.15</td>
<td>16.0</td>
<td>2</td>
<td>2.1</td>
<td>'q2'</td>
</tr>
<tr>
<td>24</td>
<td>16</td>
<td>34.96</td>
<td>+0.33</td>
<td>0.06</td>
<td>15.62</td>
<td>0.04</td>
<td>22.2</td>
<td>2</td>
<td>1.6</td>
<td>'v'</td>
</tr>
<tr>
<td>25</td>
<td>16</td>
<td>35.31</td>
<td>+0.33</td>
<td>0.06</td>
<td>17.87</td>
<td>0.17</td>
<td>16.3</td>
<td>2</td>
<td>3.8</td>
<td>'v'</td>
</tr>
<tr>
<td>26</td>
<td>16</td>
<td>36.40</td>
<td>+0.33</td>
<td>0.06</td>
<td>16.30</td>
<td>0.06</td>
<td>14.9</td>
<td>2</td>
<td>1.3</td>
<td>'v'</td>
</tr>
<tr>
<td>27</td>
<td>16</td>
<td>34.33</td>
<td>+0.33</td>
<td>0.06</td>
<td>15.60</td>
<td>0.05</td>
<td>14.3</td>
<td>2</td>
<td>1.7</td>
<td>'v'</td>
</tr>
<tr>
<td>28</td>
<td>16</td>
<td>36.15</td>
<td>+0.33</td>
<td>0.06</td>
<td>16.52</td>
<td>0.08</td>
<td>15.0</td>
<td>2</td>
<td>2.3</td>
<td>'v'</td>
</tr>
</tbody>
</table>

3 COLOUR–COLOUR DISTRIBUTIONS

3.1 Models

The detailed modelling of near-IR/mid-IR colour–colour distributions and resulting interpretations of physical properties and star formation rates of the galaxies will have to wait for more comprehensive spectral and redshift data. However, it is very informative to check the expected redshift effects on the colour–colour
Near- and mid-IR colours of star-forming galaxies

Figure 1. Examples of K-band images of the brightest and largest (in near-IR) galaxies in our sample. Positional error circles of 13 arcsec diameter have been plotted around the ISOCAM detections. The ISOCAM pixel size is 6 arcsec. Object ‘A’ is an E/S0-type galaxy; the NED data base catalogues it with a name NPM1G+41.0441 and unknown redshift. Object ‘B’ has the largest extent of our sample. It is named UGC 10459, lying at $z = 0.03$ (NED), and it is also a radio source ELAISR20 J163507+405928 (Ciliegi et al. 1999). Objects ‘C’ and ‘D’ form a galaxy pair, and ‘C’ is the brightest mid-IR source in our sample. The pair’s redshifts or classifications are not available from the literature. Object ‘E’ is known as KUG 1632+414 ($z = 0.03$) and it is also a radio and IRAS source. NED classifies it as ‘spiral’ and our near-IR image clearly shows a disc in addition to a very bright unresolved nucleus. The rest of the sources in our catalogue are much smaller.

3.2 Near-IR/mid-IR colours of ELAIS galaxies

In general, the emission from galaxies in near-IR bands is due to the stellar contribution, the 6.7 µm carries information on the PAH contribution, and any strong 15 µm emission would indicate warm dust. There are thus several colour indices that may be useful in studying the relative strengths of these components and processes. For example, the 6.7/15 µm flux ratio is expected to trace activity in the ISM of galaxies.

Figs 4 and 5 show the [6.7/15] ratio against [2.2/15] and [6.7/15]. The first compares the relative strength of the stellar and warm ISM component. Objects to the right are dominated by stellar emission, and those to the left by warm dust, while the vertical axis tells about the heating activity and the relations of PAHs and warm dust. The second figure depicts the stellar versus PAH contribution. To study the [6.7/15] ratio further, the ISOCAM bands are plotted against each other in Fig. 6, normalizing with the near-IR flux, which in addition to stellar light is expected to be a good measure of stellar mass in a galaxy (e.g. Kauffmann & Charlot 1998). The implications of this will be discussed more in Section 4.

Models presented in Section 3.1 are overplotted in all the colour–colour diagrams for the range $z = 0$ to 1. Note that the UIB features move rapidly beyond the 6.7-µm filter with redshift, which results in decreasing [6.7/15] in models including strong PAH emission.

---

2 Libraries of selected models are publicly available at http://grana.pd.astro.it/grasil/modlib/modlib.html
Figure 2. Near- to mid-IR colour as a function of $K$ magnitude ($([2.2/6.7] = f_{2.2 \mu m}/f_{6.7 \mu m}$). Those objects which are classified (morphologically) as stellar in the APS catalogue are overplotted with a cross. All the brightest objects are stars. The inset shows a detail of the region where the stellar population overlaps with galaxies (likely ellipticals). Galaxies are plotted as triangles and stars as crosses.

Figure 3. Same as Fig. 2, but showing the $K$ to 15 $\mu$m colour.

Figure 4. The $[6.7/15]$ mid-IR colour ratio versus $[2.2/15]$ colour of all ELAIS sources in our fields. Those objects which were previously defined as stars are shown as crosses. GRASIL model predictions for galaxies are overplotted. The model colours are for a range of $0 < z < 1.0$, with the largest solid symbol marking $z = 0$ and the others the positions for $z = 0.25, 0.5$ and 0.75. Average, conservative error bars are shown at the lower right corner.

Figure 5. The $[6.7/15]$ ratio versus $[2.2/6.7]$. Typical error is again indicated at lower right corner.

Active galactic nuclei (AGN) on the other hand are expected to lie at the extreme upper right in Fig. 6 owing to their steeply rising continuum (e.g. Laurent et al. 2000).

Most of the ELAIS galaxies with data in both mid-IR bands appear to group at a region where the models predict low-redshift, $z = 0.1–0.4$, late-type Sc spirals. According to the models, the near- to mid-IR SEDs of all spirals would look fairly similar at $z \sim 1$. However, it is unlikely that such objects are detected to the ELAIS survey limits.

Active galactic nuclei (AGN) on the other hand are expected to lie at the extreme upper right in Fig. 6 owing to their steeply rising continuum (e.g. Laurent et al. 2000).

The two mid-IR filters detect surprisingly different populations. As can be seen from Table 1, of the 97 identified galaxies that are
from an area covered with both mid-IR bands, only 29 are common
to both LW2 and LW3. There are 55 galaxies detected only at 15 \( \mu m \),
and 13 galaxies detected only at 6.7 \( \mu m \). For those ISOCAM sources
with a detection in only one mid-IR band, the \( J - K \) colour might
provide additional clues. For example, starbursting galaxies should
have very red \( J - K \) colours. Fig. 4 plots the \([2.2/15]\) against \( J - K \).
While there are a number of sources with a red \( J - K \), they do not
constitute a large population. More strikingly, compared to Figs 4
and 6, there are many more sources at a low \([2.2/15]\) ratio.

While the most extreme sources are too faint to acquire any def-
finite morphological information from our data, we can constrain
the nature of the sources missed in the 6.7-\( \mu m \) band by examining
detection limits. Since the 15-\( \mu m \) fluxes of the missed 51 galaxies
range from 1 to 3 mJy, typical \([6.7/15]\) ratios should be around 0.45
to be consistent with the 80 per cent LW2 completeness detection
limit. This implies Sc galaxies or starbursts around \( z \approx 0.15 \) or Sb
at \( z \approx 0.5 \). Accordingly, most \([2.2/15]\) ratios of the missed sources
(empty squares in Fig. 7) do lie by the Sc and starburst model curves.
We also derived a rough estimate for the expected 6.7-\( \mu m \) flux from
a mean correlation of \([15/2.2]\) with \([6.7/2.2]\), using the ELAIS
sources in Fig. 6 and also a comparison sample discussed below
in Section 3.3. The derived \( f_\beta(6.7 \mu m) \) are shown in Fig. 8. Galaxies
with the lowest \([2.2/15]\) ratios fall below the LW2 detection limit
while still being detected in LW3. It is thus clear that the faintest
late-type spirals and starbursts make up the majority of LW2-missed
sources. However, statistically we should find only approximately
five sources with LW2 fluxes between 1 and 2 mJy in the figure.

There are around 20, many of them with a \([2.2/15]\) ratio typical of
earlier type spirals (Sb). These might harbour some form of activity
resulting in a lower than expected \([6.7/15]\) ratio.

The objects seen in 6.7 \( \mu m \) but not in 15 \( \mu m \) are plotted in Fig. 9.

In order to compare our resulting ELAIS near- to mid-IR colours to a
local sample of galaxies observed with ISO, and to discuss how well
the galaxy types can be separated with near- and mid-IR colours,
we made use of the data sets of Boselli et al. (1998), Dale et al.
(2000) and Roussel et al. (2001a). Naturally, there exists a large
body of work performed with IRAS galaxies establishing near-
and mid-IR data bases (e.g. Spinoglio et al. 1995) – however, to avoid
complications of band conversions, we restrict ourselves only to
recent ISO data. The Roussel et al. set consists of nearby spirals, and it includes a subset of the Boselli sample, which are Virgo cluster
galaxies. The Dale et al. sample contains galaxies from the ISO US
Key Project ‘Normal Galaxies’.


\[ \text{Figure 6. The 6.7 and 15 } \mu m \text{ fluxes normalized with the } K\text{-band flux, i.e. by the}\]
\[ \text{stellar contribution to the brightness of the galaxy. The strengths of the mid-IR}\]
\[ \text{fluxes are seen to correlate strongly, and the difference in the relative strength of mid-IR}\]
\[ \text{fluxes ranges over nearly two orders of magnitude. The \textit{GRASIL} models}\]
\[ \text{are overplotted again. The bright galaxies of Fig. 1 are labelled from A to E. The dotted lines}\]
\[ \text{roughly separate areas for different types of galaxies – see Section 4.1. In addition, we have}\]
\[ \text{overplotted a hyperluminous IR galaxy (z = 1.1) detected in another ELAIS field (see}\]
\[ \text{Morel et al. (2001)) and two } \textit{potential quasars} \text{ discussed in Section}\]
\[ \text{4.3, one of which is a confirmed QSO at } z = 1.14. \text{ Typical error is shown at bottom right}\]
\[ \text{corner.} \]
Figure 7. The [2.2/15] ratio plotted as a function of $J-K$ colour. For most normal galaxies $J-K$ is expected to be between 1 and 2. Those sources which are detected in both mid-IR bands are marked with a diamond, and those which do not have LW2 coverage are marked with a cross. Most of the sources missed by the 6.7 µm survey (i.e. empty squares) have a very small [2.2/15] ratio, expected from moderate-redshift Sc and starburst galaxies as predicted by GRASIL. See Fig. 8 for more details. One confirmed QSO ($z=1.142$) is marked with a large asterisk, and 'potential QSOs' discussed in Section 4.3 are marked with large diagonal crosses. The QSO model (from Schmitt et al. 1997) curve is marked at half-redshift intervals, while other models are with 0.25 intervals, as before.

Figure 8. Galaxies detected in only one ISOCAM filter. Fluxes in the other band are derived from their expected correlation to near-IR/mid-IR ratio using models, ELAIS galaxies and local galaxies discussed in Section 3.3. The dashed vertical lines show the expected completeness levels. Those detected at 15 µm but missed in the 6.7 µm band are plotted on the left. According to [2.2/15] these galaxies should typically be Sc, starbursts and perhaps AGN. Galaxies detected in 6.7 µm but missed in the 15 µm band are on the right. Many of the missed galaxies are early types with high [2.2/6.7], though there are also QSOs included.

Figure 9. The [2.2/6.7] ratio plotted against $J-K$ colour. Some of the objects missed by LW3 seem to be nearby early-type galaxies. In fact, there are several more such cases, but they lack coverage in one or the other near-IR band. Other LW3-missed objects have low [2.2/6.7] and lie close to the QSO model curve. 'Potential QSOs' discussed later in Section 4.3, are marked with large diagonal crosses; three of these are actually catalogued quasars and are overplotted with a large cross (only one of them is detected by LW3).

The main difficulty in the comparison is the various photometric techniques used in both the near-IR and ISO data (see e.g. Spinoglio et al. 1995). A large number of the nearby galaxies have near-IR data available from NED (the NASA/IPAC Extragalactic Database). However, to have consistent photometry, we decided to use only those galaxies for which there were 2MASS data available from the second incremental data release. The 2MASS catalogue lists numerous magnitudes, of which we used the default 'fiducial circular magnitudes at 20 mag/sq. arcsec', because of the wide range of sizes and shapes of the galaxies in the comparison sample. Boselli et al. (1998) give their own near-IR photometry. We performed a cross-check of their $K$-band photometry between 2MASS values and found a fairly good consistency: apart from some Sc-type galaxies, 2MASS isophotal magnitudes were 0.15 mag fainter than the Boselli values, with a scatter of 0.31 mag. That the levels of Boselli and 2MASS magnitudes are so close, and that the sizes of galaxies in the other two samples are not significantly different from the Boselli galaxies, gives us confidence to use 2MASS magnitudes for the nearby comparison galaxies, and to compare them directly with the 'total magnitudes' of the ELAIS objects. Nevertheless, for consistency reasons with the Dale and Roussel samples, we decided to use only those galaxies from Boselli et al. which had 2MASS photometry available. In the following, with the Dale and Roussel samples we mean those galaxies from the respective original works for which we found 2MASS magnitudes. Our Boselli sample means those galaxies from Boselli et al. with 2MASS photometry, and those galaxies excluded which are already included in the Roussel sample.

As for the ISO data, the standard CAM Interactive Analysis (CIA) packages were used for preprocessing of raw data in all of the
comparison data here, as well as the ELAIS data. The ISO fluxes of all the comparison samples are calculated from maps resulting from the application of CIA/IDL procedures [see Roussel et al. (2001a) for a detailed description of the reduction process]. Fluxes in all these comparison samples were calculated using various apertures, and all claim their fluxes to represent total values at better than 20–30 per cent accuracy. There is a systematic difference by approximately a factor of 1.4 in fluxes of some galaxies common to the Roussel et al. and Dale et al. catalogues (see Roussel et al. 2001a); however, none of these are included in our subsamples. The mid-IR fluxes in Boselli et al. (1998) are not published apart from SED plots; the values were provided by A. Boselli.

As mentioned earlier, in contrast to the photometry of these comparison samples, the mid-IR ELAIS fluxes are values derived from peaks in time histories of individual pixels and corrected for PSF effects. However, we are confident that the ELAIS ISOCAM fluxes are close to the true total values (see Sections 2.4 and 2.6 and Appendix A).

4 DISCUSSION

4.1 Classifying ELAIS galaxies

Unfortunately, at present we do not have optical imaging to definitely classify our ELAIS galaxies. Classification with the help of GRASIL models was briefly discussed along with near-IR/mid-IR colours in Section 3.2. How accurate can the classification of normal galaxies be using near- and mid-IR colours? For example, Sauvage & Thuan (1994) find only loose correlations between IRAS colours and morphological type in their large sample. There would be interest in having a near-IR/mid-IR photometric classification, in anticipation of forthcoming very large galaxy surveys by, for example, SIRTF. Here we will investigate whether the comparison sample presented above has correlations between morphology and near-IR/mid-IR properties and see what these would imply for our ELAIS galaxies.

Fig. 10 shows the Roussel and Boselli samples in a mid-IR/near-IR two-colour diagram along with ELAIS sources. There is a clear trend: the type of galaxy becomes systematically later upwards along the diagonal. This should not be a great surprise, since essentially the progression shows the overall amount of emission from the ISM in the galaxy increasing. The average [15/2.2] for early types (Sa and earlier) is 0.2 whereas for the late types (Sc and later) [15/2.2] ≈ 2.2.

Fig. 11 shows the Dale sample in the same fashion. The sample covers a wide range of morphological types, but it is evident that barred galaxies are plentiful and especially galaxies that have been attached with a peculiar (‘p’) morphology in addition to a regular Hubble type. The trend seen in the Roussel and Boselli samples is not clear at all. The whole sample groups strongly towards the Sc model colour, including the morphological early-type galaxies. The peculiars (‘p’ and purely ‘Pec’) and irregulars tend to have the highest mid-IR/near-IR ratios. The Dale sample also has many more galaxies with significantly lower [6.7/15] compared to the Roussel/Boselli sample. The difference mainly comes from galaxies with high mid-IR/near-IR ratios. This is true regardless of the ~40 per cent discrepancy in the photometry mentioned earlier. The Boselli and Roussel galaxies

![Figure 10](image-url). The 6.7 and 15 μm fluxes from Roussel et al. (2001a) and Boselli et al. (1998), normalized with the K-band fluxes. Corresponding near-IR data are from 2MASS. The ELAIS data are overplotted as small crosses and the GRASIL models are shown for z = 0 only (see Fig. 6 for redshift dependence). The dashed line shows the one-to-one ratio of 15 and 6.7 μm fluxes. We have separated regions roughly corresponding to different types of galaxies with dotted lines – see text for details.
on the other hand are strongly concentrated along the one-to-one correlation line where \([6.7/15] \approx 1\), where the galaxies are supposedly dominated by quiescent ISM. We will return to this point in Section 4.2.2.

As can be seen in Figs 10 and 11, we have divided the diagram into four regions with the dotted lines: the areas roughly correspond to low-redshift early-types, Sab spirals, Scd, and ‘AGN’ [the latter class includes several types of active sources, e.g. QSOs, Seyfert nuclei, ultraluminous infrared galaxies (ULIRGs), strong starbursts]. The dividing lines in the figures can be obtained from \(\log[15/2.2] = -\log[6.7/2.2] + b\) where \(b = -1.0, 0.3\) and 1.67 starting from the lower left, respectively. The Roussel and Boselli galaxies fall very well into their areas. Disregarding blue compact dwarfs (BCDs), there are only six galaxies out of 34 in a ‘wrong’ area, and of these, five are very close to the borderlines. This classification does not work as well for the Dale sample though. We conclude that according to the nearby comparison sample the near-IR/mid-IR two-colour diagrams do discriminate between types of normal galaxies, especially those which have \([6.7/15] \approx 1\).

Where are our ELAIS galaxies in this classification? The ELAIS sample as a whole clearly groups towards the late Hubble types. However, as seen above, near-IR/mid-IR flux ratio may not be a good indication of morphological type for those galaxies with low \([6.7/15]\). Nevertheless, of the 29 galaxies in Table 2 (see Fig. 6) there are 21 galaxies in the Scd region and five in the Sab region. Two are found in the uppermost region in the far right – in Section 4.3 they are shown to be potential AGN. Only one galaxy seems to be an early type, though it does have excess 15-\(\mu\)m flux. Indeed, early-type galaxies have been shown to have widely differing amounts of dust (see Madden, Vigroux & Sauvage 1999, and references therein). ‘Traditional’ ellipticals, with no significant ISM presence, would not have been seen at all by the LW3 filter in the ELAIS survey. As shown in the inset of Fig. 2, there are several probable ellipticals that are detected only in LW2.

All the largest galaxies that show clear morphology in our data (Fig. 1, i.e. those labelled in Fig. 6) are in consistent classification areas: ‘A’ is the early-type galaxy and the rest are spirals. Object E is a disc galaxy with a very bright compact nucleus. It has the lowest \([6.7/15]\) ratio of these five bright galaxies, indicating star formation, as will be discussed next.

4.2 Tracing star formation activity

4.2.1 Star formation tracers

Much-discussed tracers of star formation include the H\(\alpha\) emission of a galaxy, the UV continuum and total far-IR luminosity. It is also well known that star formation in galaxies occurs in two very distinct places: in the discs of spirals, and in compact circumnuclear regions (for a comprehensive review, see Kennicutt 1998). In principle the mid-IR could help in solving some of the uncertainties related to the mentioned diagnostics: e.g. mid-IR is certainly less prone to extinction than UV and H\(\alpha\) studies. It could also help in determining the heating source of IR emission, which affects the accuracy of the far-IR diagnostic. The far-IR tracer is known to work well for circumnuclear starbursts – it is in the discs of normal galaxies where help would be needed.
Near- and mid-IR colours of star-forming galaxies

If the mid-IR is to be useful as a star formation rate (SFR) indicator, calibrators with the other methods are necessary because of the complexity of theoretically deriving an accurate relation between mid-IR emission and amount of young stars. Indeed, Hα emission has been shown to correlate with mid-IR luminosity in the discs of spiral galaxies (Vigroux et al. 1999; Cesarsky & Sauvage 1999; Roussel et al. 2001b). Also far-IR seems to correlate linearly with mid-IR and Hα if only discs are considered, and SFR can thus be estimated (Vigroux et al. 1999; Roussel et al. 2001b).

The relations do not hold in regions of more intense star formation (e.g. nucleus), and thus nuclear star formation could confuse a global SFR determination. Vigroux et al. and Roussel et al. argue that this is precisely the reason for non-linearity in global far-IR versus Hα relations. Thus, only limits to SFR can be calculated from integrated mid-IR luminosity, and the need for information on the proportions of disc and nuclear IR emission is highlighted.

4.2.2 Clues from \(f_\lambda(6.7\mu m)/f_\lambda(15\ \mu m)\) and near- to mid-IR

The mid-IR flux ratio is helpful in tracing the star-forming activity, as discussed before. We also expect the near-IR to add to the information. To illustrate these effects, Fig. 12 shows all those galaxies from the comparison sample discussed in Sections 3.3 and 4.1 which had IRAS fluxes available. The upper left panel shows an IRAS colour diagram and upper right the ISO-IRAS colour distribution. The lower panels plot the near-IR/mid-IR colours against the IRAS [60/100] colour. The galaxies are differentiated by morphology into ellipticals/lenticulars, discs and irregulars/peculiars – a galaxy may have both a lenticular or disc and a peculiar classification.

The previously observed trend (Helou 1999, 2000; Vigroux et al. 1999; Dale et al. 2000), that [6.7/15] first remains fairly constant and starts to drop only at a higher [60/100] level, is evident. While there is more scatter between galaxies in the near-IR/mid-IR ratios at low [60/100] values, the [2.2/15] value does (anti) correlate closely with [60/100]. In contrast, the slope of [2.2/6.7] has a break. Empirically, examining the lower panels, it is clear that the drop in [6.7/15] is caused by the stronger increase of 15-\(\mu\)m emission relative to that at 6.7 \(\mu\)m. Also, the [6.7/15] and [2.2/6.7] slopes have almost exactly inverted shapes, which results in the linear [2.2/15] versus [60/100] relation.

What then do the slopes of colour indices tell us? First of all, the nearly constant [6.7/15] at [60/100] \(< 0.4\) heating regime might imply that both mid-IR bands are dominated here by emission from a common source, namely the UIBs, as suggested by Roussel et al. (2001b). On the other hand, since the 11.3 and 12.7 \(\mu\)m UIB bands contributing to the LW3 filter are thought to be weak, it might also be a common site of the emission, rather than common physical origin, which is more important. Nevertheless, at higher heating levels the global levels of 6.7 and 15 \(\mu\)m emission clearly behave differently. A simple and common interpretation of the drop in the [6.7/15] ratio has been that, after a threshold, the heated continuum from very small grains enters the 15-\(\mu\)m band. If this were the only effect, one should expect also a break in the [2.2/15] slope, which is not seen. Since the strength of PAH emission would be expected to follow the interstellar radiation field (ISRF), the break in [2.2/6.7] could be taken to indicate the depletion of UIBs in galaxies with hottest [60/100] [see Cesarsky et al. (1996) for the effect in localized intense radiation environments]. The ISO-IRAS diagram must then be explained by both the increasing 15-\(\mu\)m emission and decreasing (relative to ISRF) 6.7-\(\mu\)m emission.

Are these effects driven mainly by differing amounts of quiescent and active media in the galaxy as a whole (as in the two-component model; Helou 1986; Dale et al. 1999), by different proportions of

![Figure 12](http://mnras.oxfordjournals.org/Downloadedfrom)
star formation happening in the disc versus the central parts (e.g. Vigroux et al. 1999; Roussel et al. 2001b), or something else? To study this in detail is beyond the scope of the present paper, and in any case cannot be done only with integrated, global values. However, it is interesting to note the trends with the morphologies. The galaxies with constant $k_{6.7}/k_{15} \sim 1$ are mainly normal disc galaxies, and, in fact, their spread in $[2.2/6.7]$ and $[2.2/7]$ is correlated with their Hubble type as already seen in Section 4.1. Those with higher $[60/100]$ span all morphological types, but stand out by having been classified as peculiar one way or another (more active nuclear regions?). Thus, it appears that at lower heating levels ($[60/100] \gtrsim 0.4$) the near-IR/mid-IR (and far-IR) colours of galaxies are driven by morphology, i.e. by the spatial distribution of the ISM. At higher $[60/100]$ the trends on the other hand follow closely the increasing radiation field, the warming dust continuum and (possibly) the destruction of PAH carriers. This is in agreement with the mid-IR/far-IR studies of Sauvage & Thuan (1994), who find the far-IR colours along the Hubble sequence to be driven by both star formation efficiency and spatial distribution of dust.

4.2.3 Nuclear star formation

As seen in Fig. 12, there are several early-type galaxies in the high $[60/100]$ region of the panels. These must have strong nuclear star formation since the mid- and far-IR colours of the galaxies are totally dominated by a starburst. However, it is interesting that the inclusion of near-IR photometry distinguishes several galaxies with high near-IR/mid-IR ratios which otherwise are tightly placed within the main group of points in the IRAS and ISO-IRAS plots. These are also all early types, but apparently not true starbursts. They simultaneously have relatively high heating levels (especially one at $[60/100] \approx 0.8$, NGC 1266) and high near-IR/mid-IR ratios, typical of more normal lenticulars. This may suggest, for example, that centrally concentrated dust is heated by the high ISRF environment found in the centres of ellipticals and lenticulars (Sauvage & Thuan 1994). However, we also note that all six galaxies at $[2.2/6.7] > 2$ (after excluding one elliptical) have signs of nuclear activity: five are low-ionization nuclear emission regions (LINERs) and one has an Sy2 nucleus. It thus seems that the use of the near-IR/mid-IR ratio picks out galaxies with weak active nuclei from the mid-IR/far-IR sequence. Galaxies that are fully dominated by an AGN are expected to have a much higher $[60/100]$. For example, the most extreme source at lower right in Fig. 12 is an AGN (NGC 4418; Roche et al. 1986; Spoon et al. 2001).

We also note that the four Dale galaxies with the lowest $[6.7/15]$ ratios are all barred early-type spirals (SB0 to SBa). They have on average $[6.7/15] \approx 0.4$, while the overall average is $\approx 0.6$. Two out of five of the strongly barred early-type galaxies have quite normal $[6.7/15]$. Though the statistics are weak, this fits very well with the findings of Roussel et al. (2001c), from a different galaxy sample, that in some early-type barred galaxies there is excess 15-µm flux due to recent star formation triggered by bar-driven gas inflows. Barred galaxies in general however do not seem to have greater star-forming activity than the non-barred cases.

4.2.4 Star formation in ELAIS galaxies

The ELAIS galaxies have on average $[6.7/15] \approx 0.67 \pm 0.27$, which indicates that the majority of them seem to be star-forming. While some of the sources might be at redshifts that warrant a significant correction to acquire the true ratio, most of the objects are expected to lie at small redshifts, $z < 0.3$. This is strongly suggested by Figs 4 and 5 (see discussion in Section 3.2). The same redshift range can also be derived from typical near- and mid-IR fluxes. The median $K$ magnitude of the galaxies with detections in both mid-IR filters is 14.1 mag, which gives an expected median redshift of $z \approx 0.15$ (Songaila et al. 1994). Flores et al. (1999) obtained spectroscopy for a deeper sample of 15-µm ISO-CAM galaxies and found a median redshift of $z \approx 0.7$. Our galaxy sample is an order of magnitude brighter, thus indicating typical redshifts of $z \approx 0.2$ or less. If only identified L3 ELAIS galaxies are considered, the median redshift could maximally be at $z \approx 0.3$. As seen, for example, from Fig. 4, $k$-corrections of Sc and starbursts decrease the $[6.7/15]$ ratio by a factor of $\sim 2$ out to a redshift of $z \approx 0.4$. The effect is much smaller for earlier types. The redshift-corrected $[6.7/15]$ ratios are thus likely to stay below the quiescent $[6.7/15] \sim 1$ value. The lowest detected $[6.7/15]$ are at $\sim 0.3$, which would indicate significant dust heating: $[60/100] \sim 0.6–0.9$, allowing for redshift effects in the 6.7-µm band.

A rough estimate of star formation rates (SFR) expected can be made utilizing relations in Roussel et al. (2001b). They found a good correlation between mid-IR emission and Hr, and thus SFR. The correlation holds only in discs of spirals, however, or globally only in galaxies where the integrated flux is dominated by the disc. From our sample, we selected quiescent and likely disc-dominated sources, i.e. those with $[6.7/15]$ close to unity and falling, which fell into the ‘Scd’ area in our classification. There are eight such sources, six of which with $K \sim 14$ mag. Assigning these a redshift of $z = 0.17$ and using blindly the SFR relations from Roussel et al. (2001b), with assumptions and filter widths therein, the average SFRs translate to $\sim 10$–30 $M_\odot$ yr$^{-1}$. Some of the fainter ELAIS galaxies would get SFRs several times this value; however, the application of the relation is highly uncertain without more information of the sources. The two remaining objects of the selected eight are those labelled ‘C’ and ‘D’, the bright galaxy pair in Fig. 1. These lie at about $z = 0.03$, and would come out with SFR ($M_\odot$ yr$^{-1}$) $\approx 7$ and 3, respectively.

Finally, we note that many of the ELAIS sources (as the pair just mentioned) appear to be part of a double or multiple system, some with disturbed morphology. Tidally triggered star formation clearly plays an important role in mid-IR studies of galaxies. We have verified this trend with deeper near-IR follow-up observations of the faintest (and blank field) ISO detections using the IRTF; the results will be discussed elsewhere.

4.3 Quasars, active galactic nuclei and extremely red objects

As shown, for example, in Laurent et al. (2000), the signature of AGN is a strong rising continuum starting already at 3 µm. Returning to Figs 6, 7 and 9, we further investigated the sources with low near-IR/mid-IR ratios, in order to check the capability of near-IR/mid-IR for AGN/QSO detection.

Making use of the APS colours, Fig. 13 shows the $R - J$ colour ($\beta$ being the POSS ‘E’ magnitude) against $J - K$. The solid symbols are the near- and mid-IR ELAIS galaxies, while we have also marked the stars with small symbols. This plot is equivalent to those used in optical/near-IR searches for (obscured) QSOs (the ‘KX method’; see Warren, Hewett & Foltz 2000; Francis, Whiting & Webster 2000; Barkhouse & Hall 2001). In general, QSOs tend to have red $J - K$ colours in contrast to a blue $R - J$ (or $B$ or $V$ instead of $R$).

We first selected from our galaxy sample those objects which had a stellar or ambiguous morphology from APS (20 objects in total; see also Figs 2 and 3). We checked each of these individually from our near-IR data, and many turned out to be galaxies. Several were,
Near- and mid-IR colours of star-forming galaxies

5 CONCLUSIONS

We have presented photometry of a subsample of the ELAIS ISO-CAM survey from the N1 and N2 fields. Our near-IR survey reaches down to \( J \approx 19 \) and \( K \approx 17.5 \). All of the 6.7 \( \mu m \) (LW2) REL = 2 sources are identified to these limits, as well as 84 per cent of 15 \( \mu m \) (LW3) REL = 2 sources. The detection efficiencies for REL = 3 sources are 88 and 35 per cent at LW2 and LW3 bands, respectively.

The near- and mid-IR stars were used, along with stellar models, to perform an accurate new calibration of the ELAIS ISOCAM data at both 6.7 and 15 \( \mu m \).

Stars were separated from galaxies using near- to mid-IR colours. At 6.7 \( \mu m \), 80 per cent of the identified ELAIS objects are stars. In contrast, at 15 \( \mu m \), 80 per cent of the near-IR identified ELAIS sources are galaxies.

Only one-third of LW3 galaxies are also detected in LW2, while two-thirds of LW2 galaxies are seen in LW3. The mid-IR survey as a whole mainly detects late-type spiral galaxies and starbursts. The faintest population of these is missed by the LW2 filter. The few objects missed by the longer mid-IR filter are most probably early-type galaxies. Simple arguments indicate that typical redshifts of the sample seen with both mid-IR bands are \( z \leq 0.2 \).

We have presented several colour-colour plots useful in studying the relative emission strengths of stellar, PAH and warm dust components in galaxies, and we discuss galaxy classification and star formation properties using the diagrams. In a \([15/2.2]\) versus \([6.7/2.2]\) plot the Hubble type of a galaxy can be roughly estimated from its position along the diagonal \([6.7/15] = 1\), which is a measure of the proportion of ISM in the galaxy. Of the near-IR identified galaxies detected with both mid-IR filters, 75 per cent fall in the Scd group. However, some of these might be earlier morphological types with significant nuclear star formation.

In the same \([15/2.2]\) versus \([6.7/2.2]\) plot the quiescent galaxies fall on the diagonal (where \([15/6.7] \approx 1\) with increasing star formation activity raising the galaxies above the one-to-one curve. The ELAIS galaxies are found to have significant star formation, as indicated by the \([6.7/15] \) tracer \( f_{6.7} / f_{15} \), which is \( 0.67 \pm 0.27 \) as well as by estimates from published relations between mid-IR luminosity and SFR. Redshift information and resolved imaging are however needed to quantify SFRs better and to decide whether the...
ELAIS galaxies are powered by strong nuclear starbursts or otherwise high star formation activity in the disc.

In quiescent galaxies, as indicated by their $[60/100]$ IRAS colour, $[6.7/15]$ remains very constant. These are also the galaxies where the classification of galaxies using near-IR/mid-IR ratios works the best. The mid-IR ratio starts to drop at hotter $[60/100]$. Using near-IR/mid-IR colours we find support for the view that both the increase of 15-µm emission and an apparent depletion of emission at 6.7 µm are responsible for the effect. At these higher $[60/100]$ levels, both $[6.7/15]$ and $[2.2/15]$ ratios (anti) correlate well with the $[60/100]$ activity level indicator, thus making them useful tracers of star formation.

The ELAIS survey covered here detects several active galactic nuclei. By selecting objects using a 'KX method' (considering optical to near-IR properties only) we pick out sources from our catalogue whose mid-IR fluxes are consistent with the objects being AGN/QSOs.

ACKNOWLEDGMENTS

We wish to thank Kalevi Mattila for very useful discussions and suggestions, and an anonymous referee for thoughtful and valuable criticism. We thank A. Boselli for providing his mid-IR fluxes. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration and the University of Minnesota. The APS databases can be accessed at http://aps.umn.edu. Aeronautics and Space Administration and the University of Minnesota, funded by the National Aeronautics and Space Administration and the National Aeronautics and Space Administration, as well as the University of Massachusetts, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Centre/California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES


Francis P. J., Whiting M. T., Webster R. L., 2000, PASA, 17, 56

APPENDIX A: CALIBRATION OF ISOCAM FLUXES USING INFRARED STARS

The ELAIS catalogue v.1.3 uses a one-to-one conversion of ADUs gain$^{-1}$ s$^{-1}$ to mJy fluxes. The ISOCAM handbook values are 2.32 and 1.96 ADU gain$^{-1}$ s$^{-1}$ mJy$^{-1}$ for the 6.7 and 15 µm filters, respectively (Blommaert 1998) – the reason for a factor of ~2 difference is the lack of source stabilization correction in ELAIS data.
Near- and mid-IR colours of star-forming galaxies

Figure A1. Stars in near-IR/mid-IR versus \( J - K \) diagram. The 6.7 and 15 \( \mu \)m fluxes of the ELAIS v.1.3 catalogue stars (crosses) have been converted assuming 1 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\). The \( K \)-band flux uses \( f_K = 6.20 \times 10^9 \times 10^{-0.4K} \) mJy and the \( J \)-band flux uses \( f_J = 1.52 \times 10^6 \times 10^{-0.4J} \) mJy. The model colours (filled squares) have been calculated from several stellar spectra templates used in the ISOCAM calibration programme. The stars range from A0 to K3 in spectral type, including giants and main-sequence stars. The reddest of our observed stars in \( J - K \) would be expected to be M stars. The solid and dashed lines are fits to the observed data and model points, respectively. From these we derive a constant correction factor of 1.22 to the 6.7-\( \mu \)m fluxes (i.e. 1.22 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\)) in panel (a). From panel (b) the conversion of 15-\( \mu \)m flux becomes 1.05 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\). Panels (c) and (d) show the fits using \( J \)-band magnitudes, instead of \( K \), and the flux calibrations become 1.24 and 1.06 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\) for the LW2 and LW3 filters, respectively.

As detailed in Serjeant et al. (2000) [see also Blommaert (1998)] – it is noted therein that the stabilization correction remains the largest single uncertainty in ISOCAM flux calibration]. In other words, starting from the handbook value of \( \sim 2 \) ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\) and correcting for the loss of flux resulting from lack of stabilization, the conversion becomes \( \sim 1 \) ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\).

However, in case of the LW3 data (Serjeant et al. 2000) find a discrepancy of a factor of 1.75 after a cross-correlation with 22 bright stars in the ELAIS fields – in that paper all 15 \( \mu \)m fluxes are thus multiplied by a factor of 2. The publicly available v.1.4 ELAIS catalogue uses the factor of 1.75 in 15-\( \mu \)m fluxes. In Missoulis et al. (1999) mid-\( \mu \)m fluxes were derived for the same stars using \( B \) and \( V \)-band bolometric magnitudes from \textit{Hipparcos} and SIMBAD, along with blackbody approximations. Correlating with observed fluxes, sensitivity factors of 0.56 and 0.70 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\) were obtained for 6.7 and 15 \( \mu \)m, respectively.

With good-quality near-IR data, rather than optical data, we potentially have a better chance of deriving the calibration factor for ELAIS data using the stars in our survey area. We would greatly reduce the uncertainty of extrapolating the optical magnitudes into mid-IR, as well as the required precision in the spectral types of stars.

To compare with observations, we make use of observationally based stellar spectra used for the extensive ISOCAM and ISOPHOT calibration programmes.\(^3\) We calculated near- and mid-IR colours of stars with a range of spectral types from these spectra. The models are estimated to be accurate within 5 per cent. In the mid-IR the fluxes were colour-corrected (maximally a 7 per cent effect) following the convention of \textit{ISO} fluxes which are determined using a constant energy spectrum (note that for LW3 the ‘reference wavelength’ is 14.3 \( \mu \)m).

From our own sample of stars, defined in Section 2.5, we use only those with the REL = 2 status. In addition, we exclude stars which have \( K < 8 \) mag, because of probable saturation in our near-IR images. Fig. A1(a) shows the stars detected at 6.7 \( \mu \)m plotted as [2.2/6.7] versus \( J - K \), with the model stars overplotted as solid symbols. From the model points one can notice a slight colour term, where the later spectral types with redder \( J - K \) have slightly lower [2.2/6.7]. Ignoring the negligible colour term, from the average difference of [2.2/6.7] ratios of observations and models, we derive a correction of 1.22 to the 6.7 \( \mu \)m fluxes of the v.1.3 ELAIS catalogue. Fig. A1(b) shows the equivalent plot for the 15 \( \mu \)m stars – there are far fewer stars here, but the overall calibration of the v.1.3 ELAIS catalogue seems quite accurate. We derive a 1.05 ADU gain\(^{-1}\) s\(^{-1}\) mJy\(^{-1}\) calibration for the LW3 data. Specifically, we do not find evidence for the factor of 2 (or 1.75) scaling used in Serjeant et al. (2000). Since we are using the same ELAIS data, from the same reduction process and the same photometric aperture corrections, the discrepancy has to come from the adopted method of extrapolating near-IR (our case) or optical magnitudes to the mid-IR. The \( J \)-band data can be used as well: panels (c) and (d) show the equivalent colour–colour plots with \( J \) flux. The calibration factors are

\(^3\) See http://www.iso.esa.es/users/expl/lib/ISO/wwwcal/cam.html/
confirmed, as we find 1.24 and 1.06 ADU gain$^{-1}$ s$^{-1}$ mJy$^{-1}$ for the LW2 and LW3 filters, respectively.

To compare with figures in Missoulis et al. (1999) and Serjeant et al. (2000), Fig. A2 shows the predicted 6.7 and 15 µm stellar fluxes (derived from the observed $K$ magnitude of the star using the corresponding model colour ratio) against the observed and recalibrated ELAIS 6.7 and 15 µm fluxes. The scatter is seen to be very small, and the relation highly linear over two orders of magnitude. We are thus confident of an accurate calibration for the ELAIS ISOCAM data.

In summary, in this paper we use the catalogue v.1.3 values for LW2 and LW3 multiplied by 1.23 and 1.05, respectively, to have the values in mJy (averages from $K$ and $J$ determination taken). The correction to conversion for LW3 is, in fact, smaller than the uncertainties related to the observed spread in mid-IR fluxes and the models, but we use it for consistency. Note that the v.1.4 ELAIS catalogue has the LW3 fluxes multiplied by 1.75, which needs to be taken into account if compared with results and plots in this paper.

This paper has been typeset from a TeX/LATEX file prepared by the author.