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

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22 October 2018

ABSTRACT

We present $J$ and $K$-band near-infrared photometry of a sample of mid-infrared 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 $\mu$m (LW2) and 15 $\mu$m (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 $K \approx 17.5$ mag. The near-to-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 further classify galaxies, as well as study star-formation. The ISOCAM ELAIS survey is found to mostly detect strongly star-forming late-type galaxies, possibly starburst powered galaxies, and it also picks out obscured AGN. The ELAIS galaxies yield an average mid-IR flux ratio LW2/LW3 = 0.67 ± 0.27. We discuss the $f_\nu(6.7\mu m)/f_\nu(15\mu m)$ ratio as a star formation tracer using ISO and IRAS data of a local comparison sample. We find that the $f_\nu(2.2\mu m)/f_\nu(15\mu m)$ ratio is also a good indicator of activity level in galaxies and conclude that the drop in the $f_\nu(6.7\mu m)/f_\nu(15\mu m)$ ratio seen in strongly star-forming galaxies is a result of both an increase of 15 $\mu$m emission and an apparent depletion of 6.7$\mu$m emission. Near-IR data together with the mid-IR give the possibility to estimate the relative amount of interstellar matter in the galaxies.

Key words: infrared: galaxies – galaxies: evolution – galaxies: star-burst – surveys – 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 which would tie together the detailed physical processes at work in stars and 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 and sub-mm regimes have become the focal point of interest in studies of galaxies, both normal and extreme objects. The near-infrared is an important region for galaxy evolution studies for several rea-
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 interstellar matter. By 5 μm the dust emission has taken over from radiation from stellar photospheres, except in most ellipticals.

Apart from the $f_{6.7}/f_{12}$ ratios of IRAS galaxies, the mid-infrared 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 spectral energy distributions of disk 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), due to the lack of understanding of their carriers. These broadband aromatic features are proposed to be the signature of Polycyclic Aromatic Hydrocarbons (PAH; Léger & Puget 1984).

The PAHs are an essential component in forming the mid-infrared $f_{6.7}/f_{12}$ colour ratio which is emerging as a tracer of star forming activity in galaxies (Vigroux et al. 1996, 1999, Sauvage et al. 1996, Dale et al. 2000, Roussel et al. 2001a, Helou 2000). The value $[6.7/12] ≈ 1$ is expected in quiescent medium and PDRs, while HII regions have $[6.7/12] < 0.5$ (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 been also shown to correlate with the IRAS $[60/100]$ colour ratio, which is a well known indicator of activity level in galaxies (Helou 2000, Dale et al. 2000, Vigroux et al. 1999). A two-component model of a galaxy as a linear combination of differing amounts of cold dust in cirrus clouds and warmer dust in HII 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 disk 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 15μm counts show a remarkable upturn below flux densities of 3 mJy and then a rapid convergence at approximately 0.4 mJy. This peak clearly requires strong (luminosity) evolution and can be a result of strong mid-IR emission features, a new population of sources, or some combination of these (Xu 2000, Elbaz 1999b, Genzel & Cesarsky 2000). To understand these results and to develop a coherent picture of early galaxy evolution, it is imperative to learn as much as possible about the more local galaxies.

The ELAIS project (Rowan-Robinson et al. 1999, Oliver et al. 2000) stands as a bridge between the very deep galaxy surveys in the infrared mentioned above, and nearby galaxy surveys (e.g. Boselli et al. 1998, Dale et al. 2000, Roussel et al. 2001a). ELAIS was the largest open time ISO-project with the driving ambitious goal to study the un-obscured star formation out to redshifts of $z \sim 1$. Source counts in the mid-IR have been published in Serjeant et al. (2000) and the far-IR counts in Efstathiou et al. (2000).

The aims of this paper are as follows: In Section 2 we present a subset of the ISOCAM ELAIS survey with near-IR follow-up observations. A central new result of this paper, the calibration of the ELAIS data is performed in Section 2.3 and in the Appendix using the stars detected in our fields. In Section 3 various near- to mid-IR colour-colour diagrams of the ELAIS galaxies are constructed and compared to evolutionary models including the UIB features in the mid-IR, and to a local ISO galaxy sample. In Section 4.1 we attempt to classify sources based on their NIR-MIR colours. Classifications such as this are expected to be helpful in the future, eg. with SIRTF and ASTRO-F data, when large numbers of galaxies with near-IR 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 (6.7μm) and LW3 (15μm) 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 southern ELAIS 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. Reliability and completeness in general of these versions of ELAIS catalogues will be discussed in more detail in Babbedge & Rowan-Robinson (2002, in preparation). Part of our near-IR survey is in the N1 ELAIS 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 April 1997 and May 1999), reduction, as well as photometry is found in Väisänen et al. (2000). The survey area is approximately 1 square degree, two thirds of it is in the ELAIS N2 region (centered at RA=16h36m00s, DEC=+41deg06′00″)

† Available at http://athena.ph.ic.ac.uk/elais/data.htm
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Figure 2. Near- to mid-infrared colour as a function of $K$-magnitude ($[2.2/6.7] = f_\nu(2.2\mu m)/f_\nu(6.7\mu m)$). 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.

and the rest in N1 (RA=16h09m00s, DEC=54 deg 40′ 00″). There is a small offset between the simultaneously observed FOVs in the $J$ and $K$ bands, resulting in slightly different source catalogues in the respective bands.

The 2MASS 2nd incremental data release (Cutri et al. 2000) partially covers the N1 and N2 regions. This allows us to directly cross-check our bright ($K < 14.5$) photometry 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 Mt.Hopkins (while deeper due to longer integration time) are, in fact, taken with a very similar telescope and instrument than the 2MASS data.

Figure 3. Same as the previous figure, but showing the $K$ to 15μm colour.

Ultimately, the matched and purged catalogue consists of 217 and 158 NIR sources matched with the LW2 and LW3 ELAIS catalogue, respectively. Of these, 53 are common to both ISOCAM filters, and due to LW2 coverage they are all in the N2 region. Table 1 gives the total number of ISO sources, the NIR indentifications and their classification per field, filter, and reliability class. Notably, all those ISOCAM sources detected in both filters were identified, as well as all LW2 sources with REL=2.

The probability of a chance appearance of eg. a $K = 17$ mag object within the 6″ search radius is 0.03, estimated from surface densities of near-IR objects (eg. Väisänen et al. 2000). More than 90 per cent of the matches are brighter than $K = 16.5$ mag – we thus conclude that the purely positional matching is highly accurate. And since we will be using only those mid-IR sources with a near-IR counterpart, we consider the sourcelist to be very reliable.

The ELAIS fields were surveyed also with ISOPHOT at 90 and 175 μm. Since the mid- to far-IR colours of ELAIS sources are discussed in another work (Morel et al. 2002, in preparation), we do not discuss them further here, except to note that 8 of our 29 galaxies with data from both ISOCAM bands and near-IR photometry, also have 90 μm fluxes available. In addition, 20 of the 29 are included in the ELAIS VLA catalogue (Ciliegi et al. 1999).

2.3 Matching of mid- and near-IR 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″, then 3″, and finally 6″ – at each step neighbours were merged if they had the same near-IR counterpart.

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-infrared. 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.
Figure 1. Examples of $K$-band images of the brightest and largest (in NIR) galaxies in our sample. Positional error circles of 13″ diameter have been plotted around the ISOCAM detections. The ISOCAM pixel size is 6″. Object ‘A’ is an E/S0-type galaxy; the NED database 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 also is 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 also is a radio and IRAS source. NED classifies it as ‘spiral’ and our near-IR image clearly shows a disk in addition to a very bright unresolved nucleus. The rest of the sources in our catalogue are much smaller.

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 PSF modeling. The adopted correction factors were 1.54 at 6.7µm and 2.36 at 15µm. The correction for the LW2 filter is more uncertain due to 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″, 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 NIR half-light radii and testing with different apertures) to get an estimate of correction factors to the mid-IR fluxes. We conclude that only 4 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 (2002, 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 labeled ‘A’, ‘C’, and ‘D’, respectively, are significantly smaller, and for these we adopt an approximate correction factor of 1.5.

2.5 Star/galaxy classification

We plot the NIR/MIR ELAIS data in Figs. 2 and 3 as a function of $K$-magnitude, using all the matched near-IR
Table 1. ISO CAM sources in the 1 sq.deg. near-IR survey area within the ELAIS N1 and N2 fields, per band and reliability parameter; R(EL)=2 stands for a ‘secure’ detection and R=3 for a ‘probable’ detection. The columns give the total number of ISO sources, number of NIR identifications, and the classification of these matches (see Section 2.5 for the classification). Total numbers for each band are also shown. The row labeled LW2/LW3 in N2 shows the numbers of sources with a detection in both ISO CAM bands. These objects were included in the respective LW2 and LW3 rows already; the breakdown by the REL parameter is not shown (however, for the galaxies these can be seen in table 2).

|        | NW1 | Identified | Stars | Galaxies |
|--------|-----|------------|-------|----------|
| LW3    | R=2 | 47         | 37    | 7        | 30       |
|        | R=3 | 59         | 12    | 1        | 11       |
| NW2    |     |            |       |          |
| LW2    | R=2 | 170        | 170   | 141      | 29       |
|        | R=3 | 53         | 47    | 34       | 13       |
| LW3    | R=2 | 68         | 60    | 19       | 41       |
|        | R=3 | 115        | 49    | 6        | 43       |
| LW2&LW3| R=2&3 | 53     | 53    | 24       | 29       |

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|        |     |            |       |          |
| NW2    |     |            |       |          |
| LW2    |     | 223        | 217   | 175      | 42       |
| LW3    |     | 289        | 158   | 33       | 125      |

and ISO CAM detections. We also matched all the sources in our field with optical data from POSS plates using the Automated Plate Scanner database (APS; Pennington et al. 1993), which includes morphological star/galaxy separation. Those objects with a stellar classification are identified as crosses in the two plots.

Stars clearly seem to lie in regions [2.2/6.7] > 2 and [2.2/15] > 10. We checked individually all objects in these regions using our NIR data and were able to correct several ambiguous and erroneous APS-classifications (typically optically faint, red objects). There are more stars in the 6.7μm matches, as expected, and there is more overlap between separate populations in the [2.2/6.7]-plot. We verified that several galaxies, likely to be nearby ellipticals, lie in this overlap region which is shown in more detail in the inset of Fig. 2. Henceforth, those objects which were morphologically verified as stellar by near-IR and/or optical data, and have either [2.2/6.7] > 2 or [2.2/15] > 10, are defined as stars. The rest are then classified as galaxies.

Several sources in the galaxies sample have a stellar APS classification. While we did not attempt a comprehensive morphological classification of the faintest near-IR sources, many of them are obviously extended objects in the NIR data, and the erroneous APS classification is just due to faintness of objects. Some of them are however point-like also in our data, and thus are potentially interesting cases, to which we will return in Section 4.3. However, this group might still include rare dust-shell stars.

It is interesting to note the proportions of stars and galaxies (see Table 1); in the near- and mid-IR matched catalogue 81 per cent 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 ISO CAM ELAIS 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 match observed near-IR and mid-IR colours to corresponding model colours of infrared standard stars, and are able to derive the flux calibration for the ELAIS ISO CAM data with better accuracy than done previously. The derivation is performed in the Appendix A: we adopt values of 1.23 and 1.05 ADU/gain/s/mJy 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 mJy. Note that the factors were not included in Figs. 2 and 3 above. (The LW3 calibration is in disagreement with the one performed in Serjeant et al. (2000), where a value of 1.75 ADU/gain/s/mJy was found.) Our values are in good agreement with the ISO CAM handbook values of 2.32 and 1.96 ADU/gain/s/mJy (Blommaert 1998), where an additional factor of 2 correction for signal stabilization has been included (see Appendix 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 ISO CAM catalogue. Using the mean MIR/NIR flux ratio for stars (see Appendix 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).

3 COLOUR-COLOUR DISTRIBUTIONS
3.1 Models

The detailed modeling of NIR/MIR colour-colour distributions and resulting interpretations of physical properties and star formation rates of the galaxies 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 diagrams. We chose to use a set of models from the GRASIL code ‡ (Silva et al. 1998). We used four evolving GRASIL SEDs (elliptical, Sa, Sb, and Sc) to compute K- and evolutionary corrections and observed colours as function of redshift, for our J- and K-bands as well as the ISOCAM filters. Appropriate filter curves were used to convolve the SEDs, and a colour-correction was performed in case of ISOCAM to be consistent with the convention of measurements (see Blommaert 1998). These four models are used in the following to compare with the data. In addition, to represent a starburst, we simply took the SED of an early-type spiral at the age of 2 Gyr, and held it constant at all epochs. In the wavelength range considered here the SED is similar to that of M82 and also not too unlike Sc’s in general (see Silva et al. 1998, Schmitt et al. 1997). The cosmology used in the plots is \( q_0 = 0.15 \) and \( H_0 = 50\text{km s}^{-1}\text{Mpc}^{-1} \), though changing this does not have significant effects in the.

‡ Libraries of selected models are publicly available at http://grana.pd.astro.it/grasil/modlib/modlib.htm

redshift ranges considered. It should also be kept in mind, that the models represent total luminosity of a galaxy, while the observations in practice are performed with a given aperture (although ‘total flux’ in photometry is attempted, as discussed above).

3.2 NIR-MIR colours of ELAIS galaxies

In general, the emission from galaxies in near-IR bands is due to the stellar contribution, the 6.7\( \mu \)m carries information on the PAH contribution, and any strong 15\( \mu \)m emission would indicate warm dust. There are thus several colour indices which may be useful in studying the relative strengths of these components and processes. For example, the 6.7/15\( \mu \)m 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 6.7/2.2. 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 vs. PAH contribution. To further study the 6.7/15 ratio, the ISOCAM bands are plotted against each other in Fig. 6, normalizing with the NIR 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 figures for a range \( z = 0 – 1 \). Note that the UIB features move rapidly beyond the 6.7\( \mu \)m filter with redshift, which results in decreasing 6.7/15 in models in-
Figure 6. The 6.7 and 15 µm fluxes normalized with the K-band flux, i.e. by the stellar contribution to the brightness of the galaxy. The strengths of the mid-IR fluxes are seen to correlate strongly, and the difference in the relative strength of mid-IR flux ranges nearly two orders of magnitude. The GRASIL models are overplotted again. The bright galaxies of Fig. 1 are labeled from A to E. The dotted lines roughly separate areas for different types of galaxies – see Section 4.1. In addition, we have overplotted a hyperluminous infrared galaxy (z = 1.1) detected in another ELAIS field (see Morel et al. 2001) and two ‘potential quasars’ discussed in Section 4.3, one of which is a confirmed QSO at z = 1.14. Typical error is at bottom right corner.

cluding strong PAH emission (especially Sc and starbursts). The colour of Sa type galaxies, on the other hand, starts to change only at z ~ 0.75. Ellipticals at zero-redshift occupy the same region as red stars, as expected.

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 ~ 1. However, it is unlikely that such objects are detected to the ELAIS survey limits. AGN on the other hand are expected to lie at the extreme upper right in Fig. 6 due 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 which 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 15µm, and 13 galaxies detected only at 6.7µm. 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. 7 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 definite morphological information from our data, we can constrain the nature of the sources missed in the 6.7 µm band by examining detections limits. Since the 15

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The derived NIR/MIR ratios 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 limit detection limit. This implies Sc galaxies or starbursts around $z \approx 0.15$ or Sb’s 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 μm 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 $f_\nu$ (6.7μm) 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 5 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’s). These might harbour some form of activity resulting in a lower than expected [6.7/15] ratio.

The objects seen in 6.7μm but not in 15μm are plotted in Fig. 7. As seen there and in Fig. 8, almost half of the LW3-missed objects appear to be ISM-deficient early types. However, since the LW3 catalogue should be more than 90 per cent complete above 2 mJy, the derived $f_\nu$ (15μm) at least for some of the galaxies might be too high. Surprisingly, two confirmed QSOs are among LW3-missed objects (see Section 4.3). However, numbers are small, and the 6.7 μm fluxes are low, close to the detection limit, so it is difficult to conclude anything definite.

3.3 Comparison sample

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 Roussel et al. (2001a), Dale et al. (2000), and Boselli et al. (1998). Naturally, there exists a large body of work performed with IRAS galaxies establishing near- and mid-IR databases (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 are galaxies from the ISO U.S. Key Project ‘Normal Galaxies’.

The main difficulty in the comparison are the various photometric techniques used both in 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. However, to have consistent photometry we decided to only use those galaxies for which there were 2MASS data available from the 2nd incremental data release. The 2MASS cata-
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Analysis (CIA) packages were used for pre-processing 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), none of these are however 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 ISO/MIR fluxes are close to the true total values (see Sections 2.4 and 2.6 and the 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 NIR/MIR colours in Section 3.4. 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 NIR/MIR photometric classification, in anticipation of forthcoming very large galaxy surveys by e.g. SIRTF. Here we will investigate whether the comparison sample presented above has correlations between morphology and NIR/MIR properties and see what these would imply for our ELAIS galaxies.

Figure 10 shows the Roussel and Boselli samples in a MIR/NIR two-colour diagram along with ELAIS sources. There is clear trend: the type of galaxy becomes systematically later upward 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.

Figure 14 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 which 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 peculiar (‘p’ and purely ‘Pec’) and irregulars tend to have highest NIR/MIR 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

![Figure 9](image-url)
Figure 10. The 6.7 and 15 µm fluxes from Roussel et al. (2001) and Boselli et al. (1998), normalized with the K-band fluxes. Corresponding near-IR data is 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.

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’s, and ‘AGN’ (the latter class includes several types of active sources e.g. QSOs, Seyfert nuclei, 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 BCDs, there are only 6 galaxies out of 34 in a ‘wrong’ area, and of these, 5 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 NIR/MIR 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, NIR/MIR 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 5 in the Sab-region. Two are found in the upper-most 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 15µm flux. Indeed, early-type galaxies have been shown to have widely

high MIR/NIR ratios. This is true regardless of the $\sim 40$ per cent discrepancy in the photometry mentioned earlier. The Boselli and Roussel galaxies 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’s, and ‘AGN’ (the latter class includes several types of active sources e.g. QSOs, Seyfert nuclei, 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 BCDs, there are only 6 galaxies out of 34 in a ‘wrong’ area, and of these, 5 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 NIR/MIR 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, NIR/MIR 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 5 in the Sab-region. Two are found in the upper-most 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 15µm 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. 6, there are several probable ellipticals which are detected only in LW2.

All the largest galaxies which show clear morphology in our data (Fig. 5, i.e. those labeled in Fig. 6) are in consistent classification areas: ‘A’ is the early type galaxy and the rest are spirals. Object E is a disk 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 $\text{H}_\alpha$ 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 disks 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 $\text{H}_\alpha$ studies; it could also help in determining the heating source of IR emission, which affects the accuracy of the FIR diagnostic. The FIR tracer is known to work well for circumnuclear starbursts - it is in the disks of normal galaxies, where help would be needed.

If the mid-IR is to be useful as a star-formation rate (SFR) indicator, calibrators with the other methods are nec-
cessary due to the complexity of theoretically deriving an accurate relation between mid-IR emission and amount of young stars. Indeed, Ho emission has been shown to correlate with mid-IR luminosity in the disks of spiral galaxies (Roussel et al. 2001b, Vigroux et al. 1999, Cesarsky & Sauvage 1999). Also far-IR seems to correlate linearly with mid-IR and Ho if only disks 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 (eg. nucleus), and thus nuclear star-formation could confuse a global SFR determination. Vigroux et al. and Roussel et al. argue that this precisely is the reason for non-linearity in global far-IR vs. Ho relations. Thus, only limits to SFR can be calculated from integrated mid-IR luminosity, and the need for information on the proportions of disk and nuclear IR-emission is high-lighted.

4.2.2 Clues from $f_{\nu}(6.7\mu m)/f_{\nu}(15\mu m)$ and near-IR 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] and [4, 5], 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 NIR/MIR colours against the IRAS [60/100] colour. The galaxies are differentiated by morphology to ellipticals/lenticulars, disks, and irregulars/peculiars – a galaxy may have both a lenticular or disk and a peculiar classification.

The previously observed trend (Helou 1999, 2000, Dale et al. 2000, Vigroux et al. 1999), 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 NIR/MIR 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 µm emission relative to that at 6.7 µm. Also, the [6.7/15] and [2.2/6.7] slopes have almost exactly inverted shapes, which results in the linear [2.2/15] vs. [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 MIR 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 12.7µm 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 µm 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 µm band. But if this were the only effect one should expect also a break in the [2.2/15] slope, which is not seen. And 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 µm emission and decreasing (relative to ISRF) 6.7 µm 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 star-formation happening in the disk vs. the central parts (eg. Roussel et al. 2001b, Vigroux et al. 1999), or something else? To study this in detail is out of 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 [6.7/15] ~ 1 are mainly normal disk galaxies, and, in fact, their spread in [2.2/15] and [2.2/6.7] is correlated with their Hubble type as already seen in Section [4, 5]. 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] ≥ 0.4) the NIR/MIR (and FIR) colours of galaxies are driven by morphology, i.e. by the spatial distribution of 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 MIR/FIR studies of Sauvage & Thuan (1994), who find the FIR 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. [14] there are several early type galaxies in the high [60/100] region of the panels. These must have strong nuclear star formation since the MIR and FIR 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 NIR/MIR 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] ≈ 0.8, NGC 1266) and high NIR/MIR 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: 5 are LINERs and one has a Sy2 nucleus. It thus seems that the use of the NIR/MIR ratio picks out galaxies with weak active nuclei from the MIR/FIR sequence. Galaxies which 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. [14] is an AGN (NGC 4418; Spoon et al. 2001, Roche et al. 1986).

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] ≈ 0.4, while the overall average is ≈ 0.6. Two out of five of the strongly barred early type galaxies have quite normal [6.7/15]. Though the
Figure 12. Comparing the IRAS [60/100] colour and star-formation tracer to near- and mid-IR colours of all the comparison sample galaxies with available IRAS fluxes. Early types (until Sa), disk galaxies, irregulars, and BCDs are plotted with different symbols. Those classified as peculiar are overplotted with squares. Note that most of the early-type Boselli galaxies had only upper limits in the IRAS data, and are not plotted (they would populate the relatively empty region at [6.7/15] > 2 in the upper right panel).

4.2.4 Star formation in ELAIS galaxies

The ELAIS galaxies have on average [6.7/15] ≈ 0.67 ± 0.27, which indicates that the majority of them seem to be star-forming. While some of the sources might be at redshifts which 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. 1 and 3 (see discussion in Section 3.2). The same redshift range can also be derived from typical NIR and MIR 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 ≈ 0.15 (Songaila et al. 1994). Flores et al. (1999) obtained spectroscopy for a deeper sample of 15 µm ISOCAM galaxies and found a median redshift of z ∼ 0.7. Our galaxy sample is an order of magnitude brighter thus indicating typical redshifts of z ∼ 0.2 or less. If only identified LW3 ELAIS galaxies are considered, the median redshift could maximally be at z ∼ 0.3. As seen e.g. from Fig. 1 K-corrections of Sc’s and starbursts decrease the [6.7/15] ratio by a factor of ~ 2 out to a redshift of z ∼ 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] ∼ 1 value. The lowest detected [6.7/15] are at ∼ 0.3, which would indicate significant dust heating; [60/100] ∼ 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 Hα, and thus SFR. The correlation holds only in disks of spirals, however, or globally only in galaxies where the integrated flux is dominated by the disk. From our sample, we selected quiescent and likely disk-dominated sources, i.e. those with [6.7/15] close to unity and falling which fell to the 'Scd' area in our classification. There are eight such sources, six of which with [6.7/15] close to unity and using blindly the SFR relations from Roussel et al. (2001b), with assumptions and filterwidths therein, the average SFRs translate to ∼ 15−30M⊙/yr. 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 labeled 'C' and 'D', the bright galaxy pair in Fig. 1. These lie at about z = 0.03, and would come out with SFR(M⊙/yr) ∼ 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
triggers 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, AGN, and EROs

As shown e.g. in Laurent et al. (2000), the signature of AGN is a strong rising continuum starting already at 3 μm. Returning to Figs. 3, 8 and 9, we further investigated the sources with low NIR/MIR ratios, in order to check the capability of NIR/MIR for AGN/QSO detection.

Making use of the APS colours, Fig. 13 shows the $R - J$ colour (R 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 $B - V$ 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, however, either point-like or too faint to classify: these ‘potential QSOs’ are overplotted with large diagonal crosses in Fig. 13 and also in Figs. 8 and 9. It is quite interesting that the majority of these do, indeed, fall by the NIR/MIR colours predicted for QSOs/AGN (note that the selection was done only by optical/near-IR colours and morphology). All the 5 potentials with 6.7μm flux have a very steep $K$ to 6.7μm gradient. Since the selection here required a POSS detection, the faintest NIR objects are excluded – for example, the three lowest empty squares in Fig. 13 at $J - K > 1.3$ are also point-like to our resolution, and have near- and mid-IR characteristics similar to the ‘potential QSOs’.

Part of our N2 region is covered by Crampton et al. (1988) quasar catalogue. Three of the ‘potential QSOs’ are found in the catalogue (and are marked with a large asterisk in the figures mentioned), which demonstrates the usefulness of the KX-method. Note that this does not rule out that other potentials, specifically among those 7 with $J - K > 1.4$, could not be QSOs due to only a partial overlap with the quasar catalogue. The two points at $R - J > 2$ are optically faint, near the APS limits, and are brought down to the ‘QSO area’ when using NIR/MIR. Three of the potentials have a very blue, star-like, $J - K$ – on the other hand they have clear mid-IR excess as evidenced by LW3.

Oddly, only two of these ‘potential QSOs’ have both ISOcam filter data available – in Figs. 8 and 9 these two are the points with the smallest NIR/MIR ratios. As seen in Fig. 8 they are indeed the two ELAIS objects which fall on the ‘AGN-area’ of our classification system (Section 4.1). The [6.7/15] ratio alone does not separate them from late-type galaxies. Those of the QSO potentials which have a LW3 detection only, are also likely candidates for Seyfert 2’s, which seem to have a suppressed $6 - 12\mu$m continuum (Spinoglio et al. 1995). Overall, QSOs have quite a large range of spectral shapes in the mid-IR (Haas et al. 2000) making detailed predictions difficult.

The reddest source in Fig. 8 has $J - K \approx 2.5$, which would qualify it as a extremely red object (ERO) candidate (eg. Cimatti et al. 1999; Scodexg & Silva 2000; Pozzetti & Mannucci 2000) – it does not have any optical counterpart to the POSS limits, making it at least $R - K > 5$. It has only a LW3 detection, but this is due to lacking coverage with LW2. Thus far EROs have been selected and studied in the optical and near-IR, and there is an interesting degeneracy in explaining their nature: their colours could signify either an old elliptical at $z > 1$, or a young, dusty star-forming galaxy. According to the GRASIL models, an elliptical would have $J - K \sim 2.5$ at $z > 2$. Ellipticals, especially distant ones, would not have been seen by the ELAIS survey, and in any case the low [2.2/15] $\approx 0.1$ colour shows the presence of significant dust emission. Thus, the mid-IR can break the degeneracy of ERO observations. A detailed search for red objects using deeper optical imaging and our near-IR data, accompanied with the mid-IR ISO-data, is thus of high importance.
5 CONCLUSIONS

1. We have presented photometry of a subsample of the ISO-CAM ELAIS 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.

2. 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\( \mu m \).

3. 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.

4. 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 \( z \leq 0.2 \).

5. 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] vs. [6.7/2.2] plot the Hubble type of a galaxy can be roughly estimated from its position along the diagonal ([15/7/15] = 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.

6. In the same [15/2.2] vs. [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 \( \left(f_\text{6.7}/f_\text{15} \right) \approx 0.67 \pm 0.27 \) as well as by estimates from published relations between mid-IR luminosity and SFR. Redshift information and resolved imaging is however needed to better quantify SFRs and to decide whether the ELAIS galaxies are powered by strong nuclear starbursts or otherwise high star formation activity in the disk.

7. 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 NIR/MIR ratios works the best. The MIR ratio starts to drop at hotter [60/100]. Using NIR/MIR colours we find support for the view that both the increase of 15\( \mu m \) emission and an apparent depletion of emission at 6.7\( \mu m \) 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.

8. The ELAIS survey covered here detects several active galactic nuclei. By selecting objects using a ‘KK-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.

6 ACKNOWLEDGEMENTS

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. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made use of the APS Catalog of POSS I, which is supported by the National Aeronautics and Space Administration and the University of Minnesota. The APS databases can be accessed at http://aps.umn.edu/.

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

| RA  | DEC  | J    | J-err | K    | K-err | S15 (mJy) | R | S0.7 (mJy) | R   | Notes |
|-----|------|------|-------|------|-------|-----------|---|------------|-----|-------|
| 1   | 16 37 34.4 | +04 52 08 | 13.22 | 0.02 | 12.20 | 0.02 | 34.3 | 2   | 37.3     | 2   | ‘C’, vla |
| 2   | 16 35 07.9 | +04 59 29 | 12.65 | 0.01 | 11.29 | 0.01 | 23.0 | 2   | 22.2     | 2   | ‘B’, fir, vla |
| 3   | 16 34 01.8 | +41 20 52 | 13.06 | 0.01 | 12.03 | 0.01 | 18.5 | 2   | 11.8     | 2   | ‘E’, fir, vla |
| 4   | 16 37 29.3 | +04 52 49 | 12.66 | 0.01 | 11.56 | 0.01 | 12.9 | 2   | 18.9     | 2   | ‘D’, fir, vla |
| 5   | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 6   | 16 37 05.1 | +41 31 55 | 15.26 | 0.04 | 14.02 | 0.04 | 8.5  | 2   | 8.5      | 2   | vla |
| 7   | 16 33 59.1 | +41 20 50 | 15.83 | 0.03 | 14.30 | 0.03 | 7.6  | 2   | 5.3      | 2   | vla |
| 8   | 16 36 08.1 | +41 05 08 | 15.51 | 0.01 | 14.57 | 0.01 | 7.6  | 2   | 7.5      | 2   | vla |
| 9   | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 10  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 11  | 16 33 59.1 | +41 20 50 | 15.83 | 0.03 | 14.30 | 0.03 | 7.6  | 2   | 5.3      | 2   | vla |
| 12  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 13  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 14  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 15  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 16  | 16 33 59.1 | +41 20 50 | 15.83 | 0.03 | 14.30 | 0.03 | 7.6  | 2   | 5.3      | 2   | vla |
| 17  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 18  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 19  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 20  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 21  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 22  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 23  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 24  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 25  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 26  | 16 35 25.2 | +04 55 43 | 14.14 | 0.03 | 12.99 | 0.03 | 37.8 | 2   | 38.4     | 2   | vla |
| 27  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |
| 28  | 16 35 05.1 | +41 10 38 | 14.83 | 0.02 | 13.83 | 0.02 | 8.1  | 2   | 4.9      | 2   | vla |

APPENDIX A: CALIBRATION OF ISOCAM FLUXES USING INFRARED STARS

The ELAIS catalogue v.1.3 uses a one to one conversion of ADUs/gain/s to mJy fluxes. The ISOCAM handbook values are 2.32 and 1.96 ADU/gain/s/mJy for the 6.7 and 15μm filters, respectively (Blommaert 1998) – the reason for a factor of ~ 2 difference is the lack of source stabilization cor-
rection in ELAIS data 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/s/mJy and correcting for the loss of flux resulting from lack of stabilization, the conversion becomes $\sim 1$ ADU/gain/s/mJy.

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-infrared fluxes were derived for the same stars using B and V-band bolometric magnitudes from Hipparcos and SIMBAD, along with blackbody approximations. Correlating with observed fluxes, sensitivity factors of 0.56 and 0.70 ADU/gain/s/mJy 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 programs. 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 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. A1a shows the stars detected at 6.7$\mu$m plotted as $[2.2/6.7]$ vs. $J - K$, with the model stars overplotted as solid symbols. From the model points one can notice a slight colour-term, where the later model stars overplotted as solid symbols. From the model detected at 6.

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$\mu$m fluxes of the v.1.3 ELAIS catalogue. Fig. A1b shows the equivalent plot for the 15$\mu$m stars – there are much less stars here, but the overall calibration of the v.1.3 ELAIS catalogue seems quite accurate. We derive a 1.05 ADU/gain/s/mJy 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 confirmed, as we find 1.24 and 1.06 ADU/gain/s/mJy 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$\mu$m stellar fluxes (derived from the observed $K$-magnitude of the star using the corresponding model colour ratio) against the observed and re-calibrated ELAIS 6.7 and 15$\mu$m 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.

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\textsuperscript{§} see http://www.iso.vilspa.esa.es/users/explib/ISO/wwwcal/cam.html/
Figure A1. Stars in NIR/MIR vs. $J - K$ diagram. The 6.7 and 15 µm fluxes of the ELAIS v.1.3 catalogue stars (crosses) have been converted assuming 1 ADU/gain/s to 1 mJy. The $K$-band flux uses $f_K = 6.20 \times 10^{-6} \times 10^{-0.4} K$ mJy and the $J$-band $f_J = 1.52 \times 10^{-6} \times 10^{-0.4} J$ mJy. The model colours (filled squares) have been calculated from several stellar spectra templates used in the ISOCAM calibration program. 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 µm fluxes (i.e. 1.22 ADU/gain/s/mJy) in panel a. From panel b the conversion of 15 µm flux becomes 1.05 ADU/gain/s/mJy. Panels c and d show the fits using $J$-band magnitudes, instead of $K$, and the flux calibrations become 1.24 ADU/gain/s/mJy and 1.06 ADU/gain/s/mJy, for the LW2 and LW3 filters, respectively.

Figure A2. Predicted stellar fluxes vs. the observed ELAIS fluxes. Panel a is for stars at 6.7 µm and b for the 15 µm stars. The predicted flux derivation uses $K$-band fluxes of stars and the $[2.2/6.7]$ or the $[2.2/15]$ ratio found from stellar models. The observed fluxes in a and b have been calibrated using the (small) differences (factors of 1.22 and 1.05, respectively) between the model and observed ratios (see the top panels of Fig. A1).