Astron. Astrophys. 342, 665–670 (1999)

ASTRONOMY AND ASTROPHYSICS

Discovery of distant high luminosity infrared galaxies

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Received 14 April 1997 / Accepted 18 September 1998

Abstract. We have developed a method for selecting the most luminous galaxies detected by IRAS based on their extreme values of R, the ratio of 60 μm and B-band luminosity. These objects have optical counterparts that are close to or below the limits of Schmidt surveys. We have tested our method on a $1079\,\mathrm{deg}^2$ region of sky, where we have selected a sample of IRAS sources with 60 μm flux densities greater than $0.2\,$Jy, corresponding to a redshift limit $z \sim 1$ for objects with far-IR luminosities of $10^{13}\,\mathrm{L}_\odot$. Optical identifications for these were obtained from the UK Schmidt Telescope plates, using the likelihood ratio method. Optical spectroscopy has been carried out to reliably identify and measure the redshifts of six objects with very faint optical counterparts, which are the only objects with $R > 100$ in the sample. One object is a hyperluminous infrared galaxy (HyLIG) at $z = 0.834$. Of the remaining, fainter objects, five are ultraluminous infrared galaxies (ULIGs) with a mean redshift of 0.45, higher than the highest known redshift of any non-hyperluminous ULIG prior to this study. High excitation lines reveal the presence of an active nucleus in the HyLIG, just as in the other known infrared-selected HyLIGs. In contrast, no high excitation lines are found in the non-hyperluminous ULIGs. We discuss the implications of our results for the number density of HyLIGs at $z < 1$ and for the evolution of the infrared galaxy population out to this redshift, and show that substantial evolution is indicated. Our selection method is robust against the presence of gravitational lensing if the optical and infrared magnification factors are similar, and we suggest a way of using it to select candidate gravitationally lensed infrared galaxies.

Key words: infrared: galaxies – galaxies: starburst – galaxies: evolution – galaxies: distances and redshifts

1. Introduction

One of the most fundamental results of the IRAS survey was the discovery of a class of galaxies that emit the bulk of their energy at far-infrared wavelengths and that have 8–1000 μm luminosities $L_{\mathrm{IR}} > 10^{12}\,\mathrm{L}_\odot$ (for $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.1$, as assumed throughout this paper). As shown by Soifer et al. (1986, 1987), these *ultraluminous infrared galaxies* (ULIGs) are a very significant population in the local universe, dominating the high luminosity end of the local luminosity function, and outnumbering local optically selected quasars by a factor of at least 2 (see Sanders & Mirabel 1996 and references therein). More recently, a number of objects with $L_{\mathrm{IR}} > 10^{13}\,\mathrm{L}_\odot$ have been identified, for which the term *hyperluminous infrared galaxies* (HyLIGs) has been proposed. The first object of this type to be discovered in an infrared-selected sample was $\mathrm{IRAS\,F10214{+}4724}$ at $z = 2.28$ (Rowan-Robinson et al. 1991a). Although this object is now known to be gravitationally lensed (Broadhurst & Lehár 1995; Close et al. 1995; Serjeant et al. 1995; Eisenhardt et al. 1996), it is a HyLIG even after the gravitational magnification has been accounted for (Downes et al. 1995). Furthermore, of the now more than 30 known objects in this class, most do not show any evidence of gravitational lensing.

The nature of the energy source powering the high bolometric luminosities of ULIGs and HyLIGs is a subject of intense debate (see e.g., Rowan-Robinson 1996 for a recent review). Since ULIGs and HyLIGs have luminosities in the range of the most powerful active galactic nuclei (AGNs), it has been proposed that they are powered by dust-embedded AGNs. Alternatively, the far-infrared (FIR) luminosity may be provided by a burst of intense star formation, with implied star formation rates $\dot{M}_* \approx 10^2$–$10^3\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, or even higher for HyLIGs. At the high end of this interval, a starburst lasting a typical 10^8 yrs would produce a stellar mass of $\sim 10^{11}\,\mathrm{M}_\odot$, comparable to the luminous mass of a typical galaxy. Therefore, if powered only by star formation, the HyLIGs form stars at the rate expected for high redshift galaxies in their formation process, undergoing an initial starburst that builds up the bulk of their stellar population. AGNs are known to be present in most of the known HyLIGs, but since the fraction of the FIR luminosity that they provide is unknown, the presence of intense star formation is not ruled out. Indeed, several lines of evidence indicate the presence of vigorous star formation in $\mathrm{IRAS\,F10214+4724}$ (Rowan-Robinson et al. 1993; Kroker et al. 1996; Green & Rowan-Robinson 1996), in addition to an embedded AGN (Elston et al. 1994; Soifer et

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al. 1995; Goodrich et al. 1996). Furthermore, since most of the known HyLIGs have been found in surveys of AGNs, the ubiquity of AGNs in known HyLIGs may be entirely a selection effect. Thus an unbiased survey for HyLIGs based on a sample of faint far-IR sources would be valuable for a reliable assessment of the nature of these objects. In addition, since HyLIGs can be observed to very significant redshifts, a determination of their number densities will strongly constrain the evolution of IRAS galaxies at these redshifts, as far as the most luminous part of the luminosity function is concerned.

In this paper we present a survey for the most luminous galaxies detected by IRAS in a $1079\,\mathrm{deg}^2$ area of sky. We discuss the sample selection process in Sect. 2 and our observation and reduction procedures in Sect. 3. The results are presented and discussed in Sects. 4 and 5, while our conclusions are summarized in Sect. 6.

2. Sample selection

We based our survey on a sample of sources selected from the IRAS Faint Source Catalog (FSC; Moshir et al. 1992). Since our project involves the optical identification of faint sources, it is important to avoid spurious FSC sources (resulting from e.g., small-scale structure in 60 μm cirrus). We therefore selected a survey area where diffuse 60 μm emission is faint (cf. the IRAS 60 μm maps presented by Rowan-Robinson et al. (1991b)). The area selected consists of the 4 hour R.A. (B1950.0) interval between 21^{h} and 1^{h}, at Dec. (B1950.0) less than $-30°$and Galactic latitude less than $-40°$. We also used a 60 μm flux cutoff of $0.2\,\mathrm{Jy}$, since below this value the FSC becomes rapidly less complete. The region selected contains 3057 60 μm FSC sources brighter than $0.2\,\mathrm{Jy}$ over an area of $1079\,\mathrm{deg}^2$. Stars and nearby galaxies were rejected by excluding all sources detected at 12 μm, leaving 2719 objects in the sample. As a further safeguard against spurious sources, we used the FSC flux quality indicators and cirrus flag, to retain in the sample only those sources with a high-quality detection at 60 μm and no confusion by cirrus. Since the spectral energy distribution (SED) of ULIGs peaks in the rest-frame 60 μm region, ULIGs at $z > 0.3$ will have flux densities rising monotonically with wavelength in the IRAS bands. Therefore the resulting sample was further reduced by retaining only sources detected at both 60 and 100 μm. However, following Clements et al. (1996), sources with $S_{100}/S_{60} > 5$ (where S_{100} and S_{60} are the 100 and 60 μm flux densities as given in the FSC) were excluded, since such cold sources most likely arise from small-scale structure in Galactic cirrus. Finally, we rejected sources with associations in other catalogs as indicated in the FSC, thus limiting our sample to 313 objects. As shown in Sect. 5, these strict selection criteria make our survey a sparse (approximately 1 in 8) but unbiased survey for infrared galaxies with $S_{60} \geq 0.2\,\mathrm{Jy}$ over the $1079\,\mathrm{deg}^2$ survey area.

In order to select from our sample the most distant objects, we define the FIR loudness R by

$$R \equiv L_{60}/L_B = S_{60}\,10^{0.4(B-14.45)}, \qquad (1)$$

(see Clements et al. 1996), where L_{60} is the 60 μm luminosity, L_B the luminosity in the B band, B the B-band magnitude, and S_{60} the 60 μm flux density in Jy. The bivariate B-60 μm luminosity function has been derived by Saunders et al. (1990), who show that R increases monotonically with L_{60}. This dependence accounts for the fact that the high luminosity cutoff of the luminosity function is much sharper in the optical regime than in the infrared. Therefore, S_{60} can be combined with the apparent B band magnitude to calculate R and hence obtain a crude estimate of the far-IR luminosity and distance of the object. An approximate B magnitude of the most luminous sources in our sample can be estimated as follows. For the cosmological parameters adopted here, a ULIG with $L_{\mathrm{IR}} = 10^{12}\,\mathrm{L}_\odot$ will have $S_{60} = 0.2\,\mathrm{Jy}$ if it is at $z \approx 0.35$. Using the bivariate luminosity function of Saunders et al. (1990), 95% of these will have $R > 10$, and they will have a mean absolute B magnitude of $-20\overset{\mathrm{m}}{.}0$, or an apparent magnitude $B \approx 21\overset{\mathrm{m}}{.}0$ at $z \approx 0.35$. At these magnitudes, sources can be identified on optical Schmidt survey plates. Furthermore, since the IRAS error ellipse for our sample sources is typically $10'' \times 30''$, and the extragalactic source density at $B < 21^{\mathrm{m}}$ is about 1000 per square degree, there is only about a 2% probability of chance superpositions at these magnitudes. Therefore, ULIGs in the FSC can be identified in optical Schmidt surveys and selected based on their L_{60}/L_B ratio. This method has been succesfully used by Clements et al. (1996), to find 91 ULIGs with a median redshift between 0.2 and 0.3, and a maximum redshift of 0.43, by selecting only $R > 10$ objects from FSC sources identified on Schmidt plates. This reasoning suggests that HyLIGs could be found in the same way, but selecting only sources with $R > 100$ (e.g., IRAS F10214+4724 has $R = 350$). However, a HyLIG with $L_{\mathrm{IR}} = 10^{13}\,\mathrm{L}_\odot$ will have $S_{60} = 0.2\,\mathrm{Jy}$ at $z \approx 1$, and a most likely $B \approx 23\overset{\mathrm{m}}{.}7$. Such sources are below the plate limit of common Schmidt surveys, while with deeper imaging the density of faint sources becomes so high, that reliable identification is no longer possible without additional information. In order to circumvent these problems we have first obtained a sample of *candidate* distant HyLIGs by selecting those sources for which no reliable identification can be found on optical Schmidt plates, or which have very faint optical counterparts. Optical follow-up (see Sect. 3) was then used to obtain the correct identifications and redshifts for the candidates. We note that the existence of faint but reliable FSC sources without optical counterparts above the typically $B_J = 22^{\mathrm{m}}$ limit of Schmidt surveys has been noted by several groups (Wolstencroft et al. 1986; Rowan-Robinson 1991; Sutherland et al. 1991; Clements et al. 1996; Oliver et al. 1996). Our programme is the first published project to systematically identify these optically faint and potentially very distant sources.

We carried out an identification programme for our FSC sources on the U.K. Schmidt Telescope southern sky survey plates, digitized using the COSMOS plate scanning machine (Yentis et al. 1992). The COSMOS catalog provides B_J magnitudes to a completeness limit of $B_J \approx 22^{\mathrm{m}}$, positions, major and minor axis lengths, position angles, and for objects with $B_J < 21^{\mathrm{m}}$ a classification as star or galaxy, based on an algorithm described by Heydon-Dumbleton et al. (1989). The identifications were performed using the likelihood ratio method (see Sutherland & Saunders (1992) for a detailed discussion). Briefly, the method assigns to every optical source a likelihood ratio

$$L = \frac{e^{-r^2/2}}{2\pi\sigma_1\sigma_2 N(<B_J)}, \tag{2}$$

where r is the distance between the FSC and optical positions in a coordinate system where the IRAS error ellipse is a circle of unity radius,

$$r = \sqrt{\left(\frac{d_1}{\sigma_1}\right)^2 + \left(\frac{d_2}{\sigma_2}\right)^2}. \tag{3}$$

In these expressions, σ_1 and σ_2 are the major and minor axes of the FSC error ellipse, d_1 and d_2 are the position differences of the optical source with respect to the FSC source projected on these axes, and $N(<B_J)$ is the density of objects brighter than the candidate object.

In calculating L, it is important to take into account possible errors in the star/galaxy classification performed by COSMOS. We noted that a number of FSC sources had counterparts with a very high value of L, which were however classified by COSMOS as stellar, but with axial ratios significantly exceeding unity. During our observing programme described in Sect. 3 we obtained B-band images of 19 of these, covering a range of magnitudes and axial ratios. In these 19 fields, we found that all objects classified as stellar by COSMOS, were in fact galaxies if they had $B_J < 18^{\rm m}$ and axial ratio exceeding 1.27. Some objects with lower axial ratios were also misclassified as stellar. We therefore reclassified all objects with $B_J < 18$ and axial ratio greater than 1.27 as galaxies. In calculating L for objects classified as galaxies, we computed $N(<B_J)$ taking into account only objects having the same classification. For objects classified as stellar or having $B_J > 20\overset{\rm m}{.}5$ (making them too faint for useful classification), the calculation of $N(<B_J)$ took into account all sources, regardless of classification. This method allows for the possibility of misclassification, while still somewhat favouring objects classified as galaxies.

In Eq. (2) the simplifying assumption is made that the position errors in the FSC are Gaussian. This assumption is approximately correct for small r, but the FSC position error distribution has wings which are stronger than Gaussian ones (Sutherland & Saunders 1992; Clements et al. 1996; Bertin et al. 1997). In order to take these wings into account, all optical sources classified as galaxies were assigned $L = 5$ if they were within $1'$ from the FSC position and had $B_J < 19^{\rm m}$.

The identification process consisted of calculating L as described above for every optical object within $2'$ of the FSC position. Following Clements et al. (1996), we consider an optical identification reliable for $L \geq 5$. Of our sample of 313 FSC sources, 302 had identifications with $L \geq 5$. Of the remaining 11, 5 were found to have $B_J < 19\overset{\rm m}{.}5$ objects within $1\overset{'}{.}25$ of the FSC positions, which present plausible identifications given the non-Gaussian wings of the FSC position error distribution. The remaining 6 had no plausible optical counterpart with $B_J < 20\overset{\rm m}{.}5$. The best "identifications" for these FSC sources had $L < 2$. These 6 sources thus form our sample of candidate HyLIGs. We note that IRAS F10214+4724, which has $B = 22\overset{\rm m}{.}5$ and is located outside the IRAS FSC error ellipse, would also have been selected by this method, if it was located within our survey area.

3. Observations and reduction

In order to obtain identifications and redshifts of our FSC sources we used the ESO Faint Object Spectrograph and Camera (EFOSC; Buzzoni et al. 1984) on the 3.6 m telescope of the European Southern Observatory at La Silla, Chile, on the nights of September 6–8, 1994. Conditions were clear but not photometric and the seeing (measured in Gunn i-band) was typically $1\overset{''}{.}5$. The detector was a 512^2 anti-reflection coated, thinned, back-illuminated Tektronix CCD with a pixel size of $0\overset{''}{.}61$ in imaging mode. Our observing strategy was as follows. First, a short (1–2 min) exposure of the field was taken in imaging mode using a B-band filter (and for some objects also in R and/or Gunn i), allowing the detection of objects several magnitudes below the COSMOS plate limit. Subsequently, long-slit spectra were taken of potential counterpart galaxies, in order of decreasing likelihood ratio L, and including galaxies above and below the COSMOS plate limit, until an emission line galaxy was found. The spectra were taken with integration times of 10 to 30 min, using the B300 and R300 grisms with a $1\overset{''}{.}5$ slit, providing a spectral resolution $\lambda/\Delta\lambda \approx 300$ from 3640 to 6860 Å (B300) or from 5970 to 9770 Å (R300). Wavelength calibration was derived from exposures of a HeAr lamp. Photometric and spectroscopic calibration was achieved by observations of the spectrophotometric standard L870−2. Flatfields were obtained from lamp exposures. Data reduction was performed using the standard long-slit reduction procedures as implemented in the IRAF package.

4. Results

Our results are summarized in Table 1. Positions refer to the positions provided by the COSMOS catalog, or for sources below the COSMOS plate limit to detections on our EFOSC images, adopting the astrometry of the COSMOS plates. Position errors are about $1''$ r.m.s. Magnitudes B_J are values provided by COSMOS, except for IRAS F21243−4501, where magnitudes are derived from our EFOSC imaging, calibrated using the COSMOS B_J magnitudes of other sources in the field. Since this procedure ignores the differences between B_J and the Bessel B filter used in EFOSC, B_J for this object is only approximate. Far-IR luminosities $L_{\rm FIR}$ have been calculated from $L_{\rm FIR} = 4\pi D_{\rm L}^2 F_{\rm FIR}$ where $D_{\rm L}$ is the luminosity distance and

$$\frac{F_{\rm FIR}}{\rm erg\,s^{-1}\,cm^{-2}} = 1.8\times10^{-11}\left(2.58\frac{S_{60}}{\rm Jy} + \frac{S_{100}}{\rm Jy}\right) \tag{4}$$

(see Sanders & Mirabel 1996 and references therein). This procedure somewhat underestimes the total far-IR luminos-

Table 1. Parameters of distant FSC sample sources

name	R.A.	Dec.	z	S_{60}	S_{100}	B_J	$L_{\rm FIR}$	R
	(B1950.0)			[Jy]	[Jy]		[L$_\odot$]	
IRAS F00320−3307	$00^{\rm h}\,32^{\rm m}\,00\overset{\rm s}{.}99$	$-33°\,07'\,44\farcs6$	0.439	0.43	0.87	$21\overset{\rm m}{.}10$	4.9×10^{12}	200
IRAS F00417−3358	$00^{\rm h}\,41^{\rm m}\,40\overset{\rm s}{.}41$	$-33°\,58'\,03\farcs0$	0.461	0.24	0.59	$21\overset{\rm m}{.}97$	3.3×10^{12}	240
IRAS F21065−3451	$21^{\rm h}\,06^{\rm m}\,33\overset{\rm s}{.}93$	$-34°\,51'\,34\farcs0$	0.329	0.36	1.55	$21\overset{\rm m}{.}54$	3.1×10^{12}	250
IRAS F21243−4501	$21^{\rm h}\,24^{\rm m}\,26\overset{\rm s}{.}05$	$-45°\,01'\,54\farcs2$	0.834	0.30	0.90	$23\overset{\rm m}{.}7$	1.9×10^{13}	1500
IRAS F22148−4013	$22^{\rm h}\,14^{\rm m}\,52\overset{\rm s}{.}07$	$-40°\,12'\,58\farcs4$	0.529	0.33	0.83	$21\overset{\rm m}{.}6$	4.4×10^{12}	240
or:	$22^{\rm h}\,14^{\rm m}\,51\overset{\rm s}{.}96$	$-40°\,13'\,02\farcs7$	0.380			$21\overset{\rm m}{.}5$	2.0×10^{12}	220
IRAS F23555−3436	$23^{\rm h}\,55^{\rm m}\,32\overset{\rm s}{.}14$	$-34°\,36'\,29\farcs3$	0.490	0.31	0.71	$20\overset{\rm m}{.}98$	4.8×10^{12}	130

ity because it does not include a K-correction. An accurate K-correction is not possible because of the lack of knowledge of the SED of the sources. However, under the assumption that the SED is similar to that of the prototypical ULIG Arp 220, we find that the underestimate introduced by Eq. (4) could be up to 50% for the most distant objects.

Notes on individual sample sources:

- IRAS F00320−3307: while classified as only one galaxy by COSMOS, this system consists of 2 interacting galaxies at $z = 0.439$. The compound spectrum shows strong [O II] 3727 Å, in addition to [Ne III] 3869 Å, [O III] 5007 Å and Hα.
- IRAS F00417−3358: the object with the highest likelihood ratio in this field, and therefore the a priori most likely counterpart, was found to be a luminous object showing [O II], [Ne III], Ca H and K absorption, and a 4000 Å break at $z = 0.461$.
- IRAS F21065−3451: the second most likely counterpart as indicated by our identification process, barely resolved at $z = 0.329$, and showing strong [O II], in addition to Hβ and [O III].
- IRAS F21243−4501: none of the possible COSMOS identifications showed emission lines, but a fainter object close to the IRAS error ellipse was found to have [Ne V] 3426 Å and [O II] at $z = 0.834$. A broad feature at the expected wavelength of Mg II 2798 Å may also be present.
- IRAS F22148−4013: spectra of two galaxies only $4\farcs5$ apart yielded redshifts of 0.380 and 0.529, based on strong [O II], Hβ and [O III] lines (for both objects) and also strong Hα, [N II] 6584 Å and [S II] 6716 and 6731 Å lines (in the object at $z = 0.380$). The two objects are of closely similar B_J magnitude. Either of these may be the correct identication, or they may both contribute part of the FSC 60 μm flux density. In either case at least one of the objects is a ULIG, but none is a HyLIG.
- IRAS F23555−3436: the most likely identication from the COSMOS plate is a distorted object outside but close to the FSC error ellipse showing [O II] and [Ne III] at $z = 0.490$.

In addition, we observed one object not in our sample of 6 candidate distant objects, IRAS F22569−5523, in order to check possible misidentification, since the only likely counterpart was classified by COSMOS as a fairly bright star with low axial ratio. However, this object is in fact a $B_J = 17\overset{\rm m}{.}86$ galaxy with a possible tail or extension towards the east, and showing [Ne III], [O II], Hβ and [O III] emission lines at $z = 0.235$. The COSMOS position for this object is R.A. (1950) = $22^{\rm h}\,56^{\rm m}\,53\overset{\rm s}{.}73$, Dec. (B1950) = $-55°\,23'\,24\farcs6$ and its far-IR luminosity is 8.8×10^{11} L$_\odot$. Accounting for the flux beyond 100 μm, this object is also a ULIG.

5. Discussion

All objects from our sample are found to have a FIR loudness $R > 100$. In contrast, the highest value of R among the $L \geq 5$ sources that were removed from the sample is 76. Therefore our approach of selecting those sources which do not have reliable counterparts above the COSMOS plate limit, or for which the counterpart is so faint that misidentification is no longer unlikely, proves to be very effective in selecting sources with extreme values of R. What is the nature of these objects? Of our sample of 6 sources, one is a HyLIG and five are non-hyperluminous ULIGs. The five non-hyperluminous ULIGs are all detected on the COSMOS plates and have $B_J < 22.0$ and $R < 250$. Their *mean* redshift $z = 0.45$ is higher than the highest known redshift of any non-hyperluminous ULIG prior to this study, indicating that our procedure is also a powerful method for selecting distant ULIGs. The HyLIG in our sample is the only object not detected on the COSMOS plates and this object has $B = 23\overset{\rm m}{.}7$ and $R = 1500$. This result confirms that HyLIGs can be found by selecting objects with extreme values of R. The main difficulty in applying this method is the large size of the IRAS position error ellipses, which precludes a direct optical identification at the faint magnitude levels expected for distant HyLIGs. However, future surveys, such as the ongoing European Large Area ISO Survey (ELAIS; Oliver 1996), and surveys with SIRTF and FIRST, and with SCUBA on the James Clerk Maxwell Telescope (JCMT) will provide substantially better positional accuracy and not suffer from this identification ambiguity. The method used here for selecting the most luminous and distant objects can be adapted directly to those surveys.

The small size of our sample, which contains only one HyLIG, precludes any detailed statistical inferences, which must await more extensive programmes using this selection and identification method, based on IRAS data or on the surveys mentioned previously. However, a number of trends in our data merit further discussion. In the first place, the detection of [Ne V] emission in the only HyLIG in our sample shows that this object contains an AGN. Thus all three IRAS-selected HyLIGs discovered so far (IRAS F10214+4724, IRAS F15307+3252 (Cutri et al. 1994; Hines et al. 1995) and IRAS F21243−4501 (this work)) contain AGNs. While the statistics for HyLIGs is still based on small numbers, the result is significant, since the [Ne V] line was not detected in any of the non-hyperluminous ULIGs in our sample, while our spectra did cover the wavelength where this line would be expected. Thus the HyLIGs form a remarkable contrast with the non-hyperluminous ULIGs, where the presence or absence of AGNs is a strongly debated issue, and direct evidence for the presence for an AGN is very scarce.

Our procedure brings about incompleteness in our sample of $R > 100$ objects in two ways: identification incompleteness and selection incompleteness. The former effect arises if objects with $R > 100$ fail to be selected by our $L < 5$ criterion, which occurs if a bright galaxy lies close to the line-of-sight to a distant FSC source, giving rise to erroneous identification with the bright galaxy. As noted in Sect. 2, the probability of misidentification in this situation is only about 2% for galaxies with $B_J < 21^{\rm m}$. Since the large majority of our $L \geq 5$ identifications have counterparts significantly brighter than $B_J = 21^{\rm m}$ (for 85% of the objects with $L \geq 5$, the counterpart has $B_J \leq 19\overset{\rm m}{.}0$), the probability of chance superpositions is much less than 2%, and the identification incompleteness can thus be neglected.

However, the sample of 313 objects used for our identification programme does suffer from selection incompleteness. Our selection method was aimed at rejecting spurious sources; however, as shown below, it must have removed a significant number of real sources from the sample as well. The relevant selection criteria are the requirement to have a high-quality 60 μm detection, no cirrus confusion, and a detection at 100 μm. While these criteria were effective at rejecting spurious detections, they also introduce a selection incompleteness, and may have rejected some distant objects. In order to assess the magnitude of this effect, we compare our sample to the FSS-z I sample described by Oliver et al. (1996). This sample has been constructed using low-cirrus regions with good IRAS 60 μm coverage and is estimated to be 99% complete for $S_{60} \geq 0.2$ Jy, which is the same flux limit as the sample described in the present paper. It contains 1931 IRAS FSC galaxies over an area of $839\,\deg^2$, giving a source density of 2.30 per deg^2. Adopting this source density as characteristic for the present survey shows that a total of 2483 expected IRAS FSC galaxies over the entire survey area should be expected, a plausible number given that, including spurious sources, our initial extragalactic sample in this area contained 2719 objects (see Sect. 2). In contrast, only 313 objects were retained in our sample of candidate objects after the strict selection criteria described in Sect. 2 had been applied. However, since none of these criteria introduces a bias in luminosity or distance, our sample is *unbiased* and our survey thus constitutes a *sparse* (approximately 1 in 8) survey of infrared galaxies with $S_{60} \geq 0.2$ Jy over the 1079 deg^2 area. Hence we can use our results to estimate a number density for HyLIGs at $z \leq 1$ of approximately 7×10^{-3} deg^{-2}, with considerable uncertainty due to the small numbers involved. We note that, adopting the local 60 μm luminosity function of Saunders et al. (1990), this estimate implies significant evolution in the infrared galaxy population to $z = 1$. Only in the unlikely case that the HyLIG detected in our sparse survey was the only $z \leq 1$ HyLIG in the entire 1079 deg^2 survey area, no evolution would be needed.

We finally note that since we are using L_{60}/L_B to select luminous objects, our selection method is robust against the presence of gravitational lensing, provided the corresponding magnification factors are similar at 60 μm and B. As a result, once a redshift and hence an infrared luminosity is available, R and $L_{\rm IR}$ may be combined to address the possibility of gravitational lensing. We illustrate the method using the lensed HyLIG IRAS F10214+4724 and the HyLIG IRAS F21243−4501, identified in the present work. As noted in Sect. 2, IRAS F10214+4724 has $R = 350$. Using the bivariate B-60 μm luminosity function of Saunders et al. (1990), we find a most likely intrinsic infrared luminosity $L_{\rm IR}^{\rm intr}$ of about $3 \times 10^{12}\,{\rm L}_\odot$. The apparent luminosity following from the redshift of 2.28 on the other hand, is $L_{\rm IR}^{\rm app} = 2 \times 10^{14}\,{\rm L}_\odot$. The large discrepancy between $L_{\rm IR}^{\rm intr}$ and $L_{\rm IR}^{\rm app}$ suggests gravitational amplification by a factor of about 60. Using the same reasoning, for IRAS F21243−4501 we find $L_{\rm IR}^{\rm intr} = 1.6 \times 10^{13}\,{\rm L}_\odot$ and $L_{\rm IR}^{\rm app} = 1.9 \times 10^{13}\,{\rm L}_\odot$. Because of the similarity of the two values, there is in this case no indication for gravitational lensing. Caution is required when applying this method, since the underlying assumption of similar magnification factors at optical and infrared wavelengths may easily be violated, as is the case in IRAS F10214+4724, where an optical magnification by approximately a factor of 100 is found (Eisenhardt et al. 1996), whereas the infrared magnification is only approximately a factor of 10 (Downes et al. 1995; Green & Rowan-Robinson 1996; Serjeant et al. 1998). Therefore the actual presence or absence of gravitational amplification must always be established by additional observations. However this method may be useful for selecting candidate gravitationally lensed sources for further study.

6. Conclusions

1. We have identified the most luminous infrared galaxies in an unbiased sample of 313 reliable extragalactic IRAS FSC sources with $S_{60} > 0.2$ Jy. Our method is based on the bivariate B-60 μm luminosity function of infrared galaxies, which implies that the most luminous objects have the highest values of R (as defined by Eq. (1)), and have optical counterparts that are so faint that they cannot be reliably identified (or are undetected) in typical Schmidt surveys. Using optical spectroscopy, we have systematically identified the optical counterparts of all of the 6 sources in our 60 μm sample that were too faint in B_J to be reliably identified on the UKST plates. Our results confirm that this method selects the galaxies with the largest values of R, so that these

galaxies are indeed the 6 most luminous infrared galaxies in our sample. Five of these are non-hyperluminous ULIGs with a mean redshift of 0.45, higher than any previously known non-hyperluminous ULIG; the remaining source is a HyLIG at $z = 0.834$.
2. The HyLIG in our sample ($\mathrm{IRAS\,F21243{-}4501}$) contains an AGN, as shown by the presence of [Ne V] emission. Hence all infrared-selected HyLIGs discovered so far unambiguously show the presence of AGNs. In contrast, none of the non-hyperluminous ULIGs in our sample show evidence for the presence of AGNs, and such evidence is rare among non-hyperluminous ULIGs in general.
3. Our method is robust against the effects of gravitational lensing if the optical and infrared magnification factors are similar. Under this assumption this method may be useful for selecting candidate gravitationally lensed sources by comparing an intrinsic luminosity (estimated from R) with the apparent luminosity (calculated from S_{60} and z).
4. Our survey constitutes an unbiased, sparse (approximately 1 in 8) survey of infrared galaxies with $S_{60} \geq 0.2$ Jy over a $1079\,\mathrm{deg}^2$ area, and the results allow an estimate of the number density of HyLIGs at $z \leq 1$ of approximately $7 \times 10^{-3}\,\mathrm{deg}^{-2}$, with considerable uncertainty due to the small numbers involved. Compared to the local luminosity function of infrared galaxies, this estimate indicates substantial evolution at the highest luminosities, except in the unlikely case that the HyLIG found in our sparse survey is the only HyLIG at $z \leq 1$ in the entire $1079\,\mathrm{deg}^2$ survey area.

Acknowledgements. This work was supported in part by the "Surveys with the Infrared Space Observatory" network set up by the European Commission under contract ERB FMRX-CT96-0068 of its TMR programme. This paper is based on observations made at the European Southern Observatory, La Silla, Chile. The Infra Red Astronomical Satellite (IRAS) was developed and operated by the Netherlands Agency for Aerospace Programs (NIVR), the U.S. National Aeronautics and Space Administration (NASA) and the U.K. Science and Engineering Council Research (SERC). The research of Van der Werf has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences.

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