The environments of hyperluminous infrared galaxies at $0.44 < z < 1.55$

D. Farrah,$^1$ J. Geach,$^{2,3}$ M. Fox,$^2$ S. Serjeant,$^4$ S. Oliver,$^5$ A. Verma,$^6$ A. Kaviani,$^2$ and M. Rowan-Robinson$^2$

$^1$SIRTF Science Center, Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91125, USA
$^2$Astrophysics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BW, UK
$^3$Astronomy Unit, Queen Mary College, Mile End Road, London E1 4NS, UK
$^4$Centre for Astrophysics and Planetary Science, School of Physical Sciences, University of Kent, Canterbury, Kent, CT2 7NR, UK
$^5$Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QJ, UK
$^6$Max-Planck-Institut für Extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany

1 November 2018

ABSTRACT
We present deep wide-field $K_s$-band observations of six Hyperluminous Infrared Galaxies (HLIRGs) spanning a redshift range $0.44 < z < 1.55$. The sample resides in a wide variety of environments, from the field to Abell 2 clusters, with a mean galaxy-HLIRG clustering amplitude of $\langle B_{gh} \rangle = 190 \pm 45$ Mpc$^3$. The range in environments, and the mean clustering level, are both greater than those seen in local IR-luminous galaxies, from which we infer that the range of galaxy evolution processes driving IR-luminous galaxy evolution at $z > 0.5$ is greater than locally, and includes mergers between gas-rich spiral galaxies in the field, but also includes encounters in clusters and hierarchical buildup. The similarity in the range of environments and mean clustering amplitude between our sample and QSOs over a similar redshift range is consistent with the interpretation where evolutionary connections between IR-luminous galaxies and QSOs are stronger at $z > 0.5$ than locally, and that, at these redshifts, the processes that drive QSO evolution are similar to those that drive IR-luminous galaxy evolution. From comparison of the HLIRG and QSO host galaxies we further postulate that a larger fraction of IR-luminous galaxies pass through an optical QSO stage at $z > 0.5$ than locally.

Key words: clusters: galaxies – galaxies: evolution – galaxies: starburst – galaxies: active – infrared: galaxies

1 INTRODUCTION

Since the discovery by the Infrared Astronomical Satellite (IRAS) in 1983 of a large population of galaxies with significant infrared (IR) emission, substantial effort has been expended on understanding the nature of the most luminous end of this IR galaxy population. These sources, termed Ultraluminous Infrared Galaxies (ULIRGs) if their IR luminosity exceeds $10^{12} L_\odot$, and HLIRGs if their IR luminosity exceeds $10^{13} L_\odot$, are found over a very wide range in redshift, with most lying at $z < 0.1$ (Soifer et al. 1984; Saunders et al. 2000), but with a significant number lying in the range $0.1 < z < 0.4$, and a few lying at higher redshifts. Although the consensus is now that ULIRGs and HLIRGs are powered by some combination of violent star formation and black hole accretion surrounded by large masses of gas and dust, the triggers for this activity, and how these galaxies evolve, are not known. Locally, ULIRGs are thought to be mergers between two or more gas-rich spiral galaxies, taking place almost exclusively in poor environments, and that a small number of these ULIRGs evolve into optically selected QSOs (Soifer et al. 1984; Leech et al. 1994; Sanders & Mirabel 1996; Rigopoulou et al. 1999; Farrah et al. 2001; Bushouse et al. 2002; Tacconi et al. 2002; Farrah et al. 2003). At higher redshifts however, the picture is less clear. It has been suggested that a greater variety of galaxy formation processes may play a role amongst ULIRGs and HLIRGs at high redshift (Farrah et al. 2002), a change which may manifest itself in their environments.

The Hyperluminous Infrared Galaxies (HLIRGs), which generally lie at $z > 0.3$, have been studied extensively since their discovery, motivated by their extreme luminosities which make them amongst the most luminous objects in the Universe. The first HLIRG to be found...
Table 1. Hyperluminous Infrared Galaxy sample

| Name              | z   | RA (2000) | Dec   | Spectrum | $m_{K_s}$ | $L_{ir}$ | Exp. time (s) | $k_{s,lim}$ | $m_{K_s}^*$ |
|-------------------|-----|-----------|-------|----------|-----------|----------|--------------|-------------|------------|
| IRAS F00235+1024  | 0.58| 09 26 06.7| 10 41 27.6| NL        | 17.05     | 13.15    | 1521         | 20.68       | 16.51      |
| IRAS P09104+4109  | 0.44| 09 13 45.4| 40 56 28.0| Sy2       | 15.00     | 13.24    | 2341         | 20.81       | 15.90      |
| IRAS F10026+4949  | 1.12| 10 05 52.5| 49 34 47.8| Sy1       | 16.85     | 14.00    | 3511         | 21.02       | 17.95      |
| IRAS F10119+1429  | 1.55| 10 14 37.8| 14 15 59.7| QSO       | 16.37     | $\sim$ 14.31| 3862         | 20.87       | 18.69      |
| LBQS 1220+0939    | 0.68| 12 23 17.9| 09 23 07.3| QSO       | 17.54     | $\sim$ 13.08| 1170         | 20.53       | 16.97      |
| IRAS F14218+3845  | 1.21| 14 23 55.5| 38 31 51.3| QSO       | 17.21     | 13.26    | 3277         | 21.15       | 18.21      |

Magnitudes are taken from the data presented in this paper. Infrared ($1 - 1000\mu m$) luminosities, given in units of bolometric solar luminosities, are taken from Rowan-Robinson (2001) and Farrah et al (2002b) and rescaled to $\Lambda = 0.7, \Omega_0 = 0.3$ and $H_0 = 70$. $k_{s,lim}$ is the faintest object detected by SExtractor for each field. $m_{K_s}^*$ was derived from Pozzetti et al (2003) for the redshift of each object.

(P09104+4109, at $z = 0.44$) was a cD galaxy in the core of a rich cluster, identified to have extreme IR emission by Kleinmann et al (1988), with a far infrared luminosity of $1.5 \times 10^{13} h_{50}^{-2} L_\odot$. Then, in 1991, Rowan-Robinson et al (1991) identified F01214+4724 at $z = 2.286$, with an apparent far infrared luminosity of $3 \times 10^{13} h_{50}^{-2} L_\odot$. Later observations revealed a large mass of molecular gas ($10^{12} h_{50}^{-2} M_\odot$) (Brown & vanden Bout 1991; Solomon, Downes & Radford 1992), a Seyfert emission spectrum (Elston et al. 1994), and evidence for lensing with a magnification of about 10 in the infrared (Graham & Lin 1993; Broadhurst & Lehar 1996; Eisenhardt et al 1996; Green & Rowan-Robinson 1997). These objects appeared to presage a new class of infrared galaxy.

Later observations of larger samples of HLIRGs uncovered a more detailed picture. Hubble Space Telescope (HST) imaging (Farrah et al. 2002a) revealed that a wide range of morphologies are present in the HLIRG population, from merging systems to QSOs in apparently relaxed systems. X-ray, IR, and sub-millimetre observations showed that, in all cases, HLIRGs are powered by a mixture of dust-enshrouded black hole accretion and violent star formation, with inferred star formation rates of $\geq 500 M_\odot$ yr$^{-1}$ (Rowan-Robinson 2000; Verbun et al. 2002; Farrah et al. 2002; Wilman et al. 2003), suggesting that HLIRGs are comprised of both mergers between gas-rich spiral galaxies, and young galaxies going through their maximal star formation epochs whilst harbouring an AGN.

Despite this progress, the role of HLIRGs in the broader picture of galaxy and AGN evolution remains unclear. It is not known whether HLIRGs as a class are a simple extrapolation of the local Ultraluminous Infrared Galaxies (ULIRGs, $L_{ir} > 10^{12} L_\odot$) making them mostly mergers between gas-rich spirals, or whether a wider range of galaxy formation processes play a role in HLIRG evolution. Also, the links between HLIRGs and QSOs at comparable redshifts are not well understood. Locally, it is thought that some fraction of ULIRGs evolve into optically selected QSOs (Sanders et al. 1988; Farrah et al. 2001; Tacconi et al. 2002), but it is not known whether this is also true in the distant Universe.

Many of these unknowns result from two major obstacles in studying HLIRG evolution. Firstly, HLIRGs contain very large masses of gas and dust, making observations of the galaxies themselves at all wavelengths (except perhaps the far-infrared and sub-millimetre) prone to obscuration bias. Secondly, the presence of a luminous starburst and AGN in all HLIRGs means that observations will be affected by the orientation of the HLIRG relative to us. These problems can however be partly overcome by examining the environments of HLIRGs. Since the determination of environments is independent of orientation and dust content, they are a useful tool in studying AGN evolution, and have been used extensively in studying both normal and active galaxies (Longair & Seldner 1979; Yee & Green 1987; Hill & Lilly 1991; Loveday et al. 1992; Wold et al. 2000; McLure & Dunlop 2001; Sanchez & Gonzalez-Serrano 2002). Studying the environments of HLIRGs therefore can help clarify the relations between HLIRGs and other AGN classes.

In this paper, we investigate the environments of six HLIRGs, using deep wide field $K_s$-band imaging. Observations are described in §2 and analysis is described in §3. Results are presented in §4, with discussion in §5. Finally, our conclusions are summarized in §6. Unless otherwise stated, we assume $\Lambda = 0.7, \Omega_0 = 0.3$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 OBSERVATIONS

We selected for observation six HLIRGs from the sample presented by Rowan-Robinson (2000). The sample, their redshifts and other basic data are presented in Table 1.Five of these objects were selected to lie approximately in the redshift range $0 < z < 1.6$, where the greatest evolution in the IR galaxy population is thought to occur (e.g. Rowan-Robinson et al. 1997). Additionally, we observed one further HLIRG, P09104+4109, which lies at $z = 0.44$ and is already known to lie in a rich cluster, to act as a control for our observation and analysis methods, though we do not include this source in the discussion. None of our targets show any evidence for significant gravitational lensing.

Observations were made on 25-26th December 2001 using the INGRID wide field near-infrared imager and a $K_s$-band filter, on the 4.2m William Hershel Telescope (WHT). INGRID is a 1024$^2$ pixel array, with a scale of 0.238 $''$ pix$^{-1}$, corresponding to a field-of-view of $\sim 17'$.$'$ At the redshifts of our sample this corresponds to a physical field-of-view of $\sim 1.36$ Mpc. The targets were centred approximately in the INGRID field-of-view, with exposure times selected to reach a minimum depth of $M_{K_s}^* + 2$ at the redshift of each object. Observing conditions were generally good, with little cloud cover and seeing of $\sim 0.8''$, however the atmospheric stability was variable, resulting in non-photometric nights.
The environments of hyperluminous infrared galaxies at $0.44 < z < 1.55$

The total exposure time for each object was divided into several nine point ‘box’ dither patterns, with a 16.7″ offset between each position, to allow the subtraction of cosmic rays, hot pixels, and the infrared sky background. As the INGRID field of view is too small to reliably estimate field galaxy counts from the edges of the HLIRG fields, separate control fields were also observed, with similar galactic latitudes and exposure times as the sample. For photometric calibration we observed a selection of infrared standard stars throughout each night, at several different airmasses.

3 DATA REDUCTION

Following debiasing and flatfielding, the data were reduced using our own custom-written IRAF pipeline, based in part on the Quicklook INGRID data reduction pipeline from the Isaac Newton Group (ING). As the exposure time at each position in the dither pattern was only 30 seconds, particular care was taken in accounting for bright sources when subtracting sky noise. Source masks were created for the individual frames in each dither pattern by first creating an approximate estimate of the sky by median combining the nine frames in each dither pattern without applying the dither offsets. This ‘dummy’ sky frame was then subtracted from each frame in the dither pattern to reveal the brightest sources, which were then masked out when creating the ‘real’ sky frame. The nine frames in each dither pattern were combined using the IRAF task IMCOMBINE, with dither offsets calculated by centroiding two or more bright sources common to each frame. After each dither pattern was combined into a single image, sky subtraction was performed using the ‘real’ sky frames and pixel masks described earlier. It was found that this sky subtraction method worked well in dealing with variations in the infrared sky between different dither patterns, over the long exposure time for each object. The combined images from each dither pattern were then stacked together to produce a final image $I$:

$$I = \frac{\sum_i (I_i \sigma_i^{-2})}{\sum_i \sigma_i^{-2}}$$

(1)

where $I_i$ and $\sigma_i$ are the individual images from each dither pattern, and their standard deviations, respectively. The standard deviations were derived from the noise fluctuations in each image. Noisy edges, where the total exposure time were shorter due to the dither pattern, were clipped off. The resulting field of view, at 13′ $\times$ 13′, was still sufficient to quantify the environments of the sample. The final images were of excellent quality, and flat to better than 1% across the width of the frame, and were in all cases of much higher quality than the images from the Quicklook reduction. Our reduction pipeline, ‘INREP’, is available for general use via the Isaac Newton Group (ING) web pages 1.

Sources were extracted and catalogued using the SExtractor package (Bertin & Arnouts 1996). For source extraction, we adopted the conservative criterion that a source constitutes at least four contiguous pixels, with a significance of detection of at least 3$\sigma$ above the background. The default SExtractor extraction filter was used to detect faint extended objects, with 32 de-blending thresholds, a cleaning efficiency of 1 and a contrast parameter of 0.005. The background estimation was mesh based, with a mesh size of 64 and a filter size of 3. As many of the sources in the frames were faint and slightly extended, the magnitudes were calculated using corrected isophotal (ISOCOR) magnitudes within SExtractor. The calibration zeropoint magnitudes for each object were determined from the Gaussian fits to the source profiles in the control frames.

The environments of hyperluminous infrared galaxies at $0.44 < z < 1.55$

To perform this conversion, the $A_{gh}$ statistic is evaluated:

$$A_{gh} = \frac{N_T - N_B}{N_B} - 3 - \frac{7}{2} \theta^{\gamma-1}$$

(4)

where $N_T$ is the total number of galaxies within a radius $\theta$ around the target, corresponding to 0.5 Mpc at the target redshift, and $N_B$ is the number of galaxies within the

1 http://ing.iac.es/Astronomy/Ingrid
same radius in the control field for that object. We make the assumption that \( \gamma = 1.77 \). The precise choice of \( \gamma \) will however not affect the derived clustering amplitudes, as it has previously been shown that \( B_{gh} \) is insensitive to the choice of \( \gamma \), as long as \( \gamma \approx 2 \).

The \( B_{gh} \) statistic can now be calculated, and normalised to the integral LF, \( \Phi(m_1, z) \) which represents the number of galaxies more luminous than \( m_1 \) per unit co-moving volume at redshift \( z \):

\[
B_{gh} = \frac{\rho_g A_gh}{\Phi(m_1, z)} d^3_d \delta^3 \gamma^3
\]

where \( \rho_g \) is the average surface density of background galaxies, \( d_d \) is the angular diameter distance to the target and \( \gamma \) is an integration constant:

\[
\gamma = \frac{2 \gamma}{\gamma - 1} T^2((\gamma + 1)/2) \Gamma(\gamma) \sim 3.78
\]

The integration to \( \Phi(m_1, z) \) is performed by taking a uniform LF of the form \( \phi(L) \sim (L/L^*)^\alpha \exp(-L/L^*) \) (7) and integrating down to the completeness limit at the target redshift \( L(m_1, z) \):

\[
\Phi(m_1, z) = \int_{L(m_1, z)}^\infty \phi(L)dL
\]

For the parameters used in the LF, we use the most recent determination of the high redshift near-IR LFs as given by Pozzetti et al (2003), who have determined the evolution of the near-IR LF in the \( J \) - and \( K_s \) -bands in redshift bins of \( z = (0.20, 0.65) \) and \( z = (0.75, 1.30) \), using a spectroscopic survey of a magnitude limited sample of galaxies with \( K_s < 20 \). In terms of absolute magnitudes the luminosity function can be expressed as:

\[
\phi(M) = C f(M)^{(\alpha + 1)} \exp(-f(M))
\]

where the constant \( C = 0.4 \ln(10) \phi^* \), and:

\[
f(M) = 10^{0.4(M - M^*)}
\]

As some of the galaxies in our sample lie outside of the redshift bins given by Pozzetti et al (2003), we must make assumptions as to the nature of the LF at these magnitudes. In the redshift range \( 0.2 < z < 0.65 \), we have assumed \( \alpha = -1.25 \), \( M^* = -25.64 \) and \( \phi^* = 6.11 \times 10^{-4} \text{Mpc}^{-3} \). In the redshift range \( 0.75 < z < 1.55 \) we have assumed \( \alpha = -0.98 \), \( M^* = -25.54 \) and \( \phi^* = 9.98 \times 10^{-4} \text{Mpc}^{-3} \). We note that Pozzetti et al (2003) find only mild evolution in the \( K \) -band luminosity function over the redshift range \( 0 < z < 1.3 \), hence our use of their luminosity function at \( z = 1.55 \) is unlikely to be a major source of error.

The errors in \( A_{gh} \) and \( B_{gh} \) were calculated following the prescription given by Yee & Lopez-Cruz (1994):

\[
\frac{\Delta A_{gh}}{A_{gh}} = \frac{\Delta B_{gh}}{B_{gh}} = \frac{\sqrt{(N_T - N_B)^2 + 1.3^2 N_B}}{N_T - N_B}
\]

which is based only upon (non-Poissonian) counting statistics. Other systematic errors are discussed in §5.

To compute the \( N_{0.5} \) statistic, we follow the procedure described by Hill & Lilly (1991). This statistic is computed by counting all sources within a 0.5 Mpc radius of the target, with a magnitude in the interval \( (m, m + 3) \), where \( m \) is the magnitude of the target. Subtracted from this number is the expected number of background field galaxies in the same magnitude interval calculated from the control fields. The resulting number is the \( N_{0.5} \) statistic. This measurement does not require integration of a luminosity function, although if the luminosities of HLIRGs and cluster galaxies evolve very differently with redshift then the \( N_{0.5} \) statistic will give inaccurate results. There is no evidence why this should be a major effect however, so we do not take it into account. From Table 2 the limiting magnitude for each object is fainter than \( m_{HLIRG} + 3 \) except for two cases; the image for F10119+1429 reaches \( m_{HLIRG} + 2.18 \), and the image for F14218+3845 reaches \( m_{HLIRG} + 2.94 \). In both these cases however the limiting depth is sufficiently near \( m_{HLIRG} + 3 \) that the \( N_{0.5} \) statistic is still usable.

5 RESULTS

5.1 Clustering statistics

Images of the fields around each HLIRG are presented in Figure 1. In Figure 2 we plot the galaxy counts in a 0.5Mpc region around each HLIRG, and the counts for the associated control field. The \( B_{gh} \) and \( N_{0.5} \) statistics for each object, and their errors, are given in Table 2. We also quote the approximate Abell classes of our sample in this table, based on the conversions given by Hill & Lilly (1991), in our cosmology. We note however that these conversions are arbitrary, and hence we base our quoted Abell classes on both the \( B_{gh} \) and \( N_{0.5} \) statistics.

A wide variety of environments can be seen amongst
The environments of hyperluminous infrared galaxies at $0.44 < z < 1.55$. 

Figure 1. $K_s$-band images of the fields around each HLIRG. An arrow indicates the HLIRG. Large tick marks correspond to $25''$. L-R: (top row) F00235+1024 and P09104+4109, (middle row) F10026+4949 and F10119+1429, (bottom row) LBQS1220+0939 and F14218+3845.
Figure 2. Galaxy counts in a circular region 0.5Mpc in radius around each HLIRG. The solid line shows the counts in the field around the HLIRG, and the dashed line shows the counts in the control field. L-R: (top row) F00235+1024 and P09104+4109, (middle row) F10026+4949 and F10119+1429, (bottom row) LBQS1220+0939 and F14218+3845. Error bars have been omitted for clarity.
the objects in the sample. P09104+4109 resides in an Abell 2 cluster, in agreement with previous results [Hines & Will 1993]. For the remaining objects, three reside in poor environments, and two, F10026+4949 and F10119+1429, reside in clusters, of Abell class 1 and 0 respectively, though we note that the detection of clustering for F10119+1429 is marginal, at \( \sim 2.5\sigma \). Excluding P09104+4109, the error weighted mean clustering amplitude for the remaining 5 objects is \( \langle B_{gh} \rangle = 190 \pm 45 \text{Mpc}^{-2} \).

We can compare the values of \( N_{0.5} \) and \( B_{gh} \) to each other, as these quantities have been used by many previous authors, and a well defined relation has been found between them. [Hill & Lilly 1991] derive \( B_{gh} \propto 30 N_{0.5} \). In Figure 3 we plot this relation, together with \( B_{gh} \) vs. \( N_{0.5} \) for the objects in our sample, and the conversions between \( B_{gh} \) and Abell class given by [Hill & Lilly 1991]. We also plot the best fit linear relation between \( B_{gh} \) and \( N_{0.5} \) for our data. The best fit is well matched to the relation derived by [Hill & Lilly 1991] and the objects in the sample follow this relation closely, hence we conclude that our computed values of \( N_{0.5} \) and \( B_{gh} \) are reasonable.

5.2 Error budget

The errors quoted in Table 2 for the \( B_{gh} \) and \( N_{0.5} \) statistics are only the counting errors, and do not include three further, potentially important sources of error. In this section, we discuss these three error sources in turn.

The first of these is the luminosity function assumed in calculating the \( B_{gh} \) statistic. Due to the uncertainties in the high redshift \( K_s \)-band LF used in this paper, this is an important issue to address. [Yee & Lopez-Contreras 1992] have examined the sensitivity of \( B_{gh} \) to the form of the LF, and find that an error in the assumed value of \( M^* \) of up to \( \pm 0.3 \) will still yield essentially the same results. Similarly, an error in \( \alpha \) of up to \( \pm 0.3 \) will only affect \( B_{gh} \) by at most \( \sim 20\% \). Although the \( K \) band LF is not well constrained at the redshifts of our targets, we do not expect that the true LF differs from our assumed LF by such gross margins, and therefore we conclude that uncertainties in our computed \( B_{gh} \) statistics due to the assumed LF are at most 10%.

The second of these error sources is the method used to compare the data to the luminosity function in calculating the \( B_{gh} \) statistic. This can be done in two ways. The data can be \( k \)-corrected to the rest-frame \( K_s \)-band, and compared to the \( K_s \)-band luminosity function given by [Pozzetti et al 2003], or the data can be compared directly to the J band luminosity function presented by [Pozzetti et al 2003], without applying a \( k \)-correction, as observed frame \( K_s \)-band approximately samples rest-frame J band at the redshifts of our sample. Both methods have advantages and disadvantages; the rest-frame \( K_s \)-band is a less contaminated tracer of evolved stellar mass than the J band, but suffers from the extra uncertainties introduced by applying \( k \)-corrections. Although we chose to \( k \)-correct our data to the rest-frame \( K_s \)-band, we also examined the effect of comparing our data directly to the rest-frame J-band luminosity function, without applying \( k \)-corrections. We computed \( B_{gh} \) and \( \sigma_{B_{gh}} \) without applying \( k \)-corrections, and using the J-band luminosity function from [Pozzetti et al 2003], and found that the \( B_{gh} \) values were within 1\( \sigma \) of the values computed using \( k \)-corrections and the \( K_s \)-band luminosity function for all the objects except F10119+1429, which was within 1.5\( \sigma \). Furthermore, each object still resided within the same type of environment as before, with P09104+4109, F10026+4949 and F10119+1429 residing in clusters (with the same significance of detection of clustering) and the other 3 objects lying in the field. The values of \( B_{gh} \) and \( \sigma_{B_{gh}} \) were however in all cases slightly higher using the J-band luminosity function and no \( k \)-corrections, with F10026+4949 and F10119+1429 predicted to (just) lie in Abell 2 clusters. We conclude that using the \( K_s \)-band luminosity function with \( k \)-corrections, or just the J-band luminosity function, will not significantly change our results, and that our choice of using the \( K_s \)-band luminosity function with \( k \)-corrections was the most conservative.

The third of these error sources is the choice of cosmology. Whilst both \( B_{gh} \) and \( N_{0.5} \) are relatively insensitive to the choice of \( \Lambda \) and \( \Omega_0 \), the sensitivity to \( H_0 \) is marked, particularly in the range \( 65 < H_0 < 80 \). This is illustrated in Figure 4, where we have plotted \( B_{gh} \) as a function of \( H_0 \) for F10026+4949. By varying \( H_0 \) over a relatively small range, the effect on \( B_{gh} \) is dramatic, changing from \( B_{gh} \sim 350 \) to \( B_{gh} \sim 800 \) for \( H_0 \geq 75 \). Most current measurements of \( H_0 \) produce values in the range 70 to 75, albeit with a significant error ([Freedman et al 2001] and references therein). Our adopted value of \( H_0 = 70 \), and therefore our derived clustering amplitudes, are therefore conservative.

In summary, we conclude that, whilst there are further, significant sources of error than the Poisson errors on the derived clustering statistics, none of these sources of error should significantly change our results. Furthermore, we have in all cases adopted the most conservative method possible in computing the clustering amplitudes, making it...
6 DISCUSSION

6.1 The hyperluminous phenomenon at low and high redshift

Our sample of five objects (excluding P09104), although small, exhibit a wide variety of environments, from poor environments to Abell $\sim 1$ clusters. This strongly suggests that there is a wide variety of environments amongst objects with high levels of IR emission at $z \sim 1$ generally, although a larger sample would be required to confirm this. This variety of environments is not seen amongst local ULIRGs, which are generally not found in rich environments (Sanders & Mirabel 1996). The mean environmental richness of our sample, at $\langle B_{gg} \rangle = 190 \pm 45$ Mpc$^{-1}$, is higher, at just over 3σ significance, than the galaxy-galaxy correlation statistic both locally (Loveday et al 1995; Guzzo et al 1997) and at moderate redshifts (Hudon & Lilly 1996), though we note that the latter study measured values of $B_{gg}$ up to redshifts of only $z \sim 0.5$. We infer that, in going from $z \sim 0$ to $z \sim 1$ the environments of IR-luminous galaxies become more diverse, and that the mean environment becomes richer than that of normal galaxies both locally and at moderate redshifts. This is supportive of the idea that a wider variety of galaxy formation processes are important amongst the IR-luminous galaxy population at high redshift than locally, such as hierarchical buildup or encounters in clusters. Indeed, one object in our sample, IRAS F10026+4949, may be an example of such a galaxy. This source harbours both a starburst and an AGN (Farrah et al 2002a), and lies in a rich cluster. From HST imaging, this source also possesses multiple very close companions (Farrah et al 2002b). It is thus an excellent candidate for being a CD galaxy in the process of formation in a cluster at $z \sim 1.12$, and may be the higher redshift analogue of the clustered IR-luminous active galaxies P09104+4109 and P18216+6419 (Schneider et al 1992; Hines & Wills 1993; Wold et al 2003).

6.2 Comparison to Quasar environments

Since environments are independent of orientation, we can compare the environments of our sample to those of other classes of active galaxies at comparable redshifts to examine possible relationships between HLIRGs and other AGN classes. The environments of AGN over a wide redshift range have been studied by many authors in efforts to disentangle the myriad AGN taxonomy. Radio Loud QSOs (RLQs) and Radio Galaxies (RGs) are found in a diverse range of environments, from the field to Abell Class 2 and greater, at both low and high redshift (Longair & Seldner 1973; Yee & Green 1987; Prestage & Peacock 1988, 1990; Hill & Lilly 1991; Allington-Smith et al 1993; Zirbel 1995; Wold et al 2000; Sanchez & Gonzalez-Serrano 2002). Overall, RLQs and RGs appear to prefer moderately rich environments on average, of around Abell Class 0. Determining whether or not there is evolution in the environments of RLQs or RGs with redshift is difficult, due to gravitational lensing and selection biases, but from recent results it appears that there is no significant difference in RLQ and RG environments at $z < 1.0$ (Wold et al 2000). For Radio Quiet Quasars (RQQs) a broadly comparable picture has now emerged. RQQs are found in a similarly diverse range of environments to RLQs, from the field to Abell Class 2 or richer, over a wide redshift range (Yee & Green 1987; Dunlop et al 1993; Fisher et al 1996; Deltorn et al 1997; Tanaka et al 2000; McLure & Dunlop 2001). Indeed, the most recent results, based on deep optical imaging, show that the environments of RQQs and RLQs at moderate redshifts are statistically indistinguishable (Wold et al 2003). At $z \geq 1$ there is as yet no clear consensus, but the environments of RLQs and RQQs at these redshifts do not appear to be significantly different (Huntzen, Romanishin & Valdes 1991; Hutchings, Crampton & Johnson 1995; Hutchings 1995).

In the local Universe, it was initially suggested that ULIRGs as a class are precursors to optically selected QSOs, although later results show that this is probably true for only a small subset of the ULIRG population (Sanders et al 1988; Farrah et al 2001; Tacconi et al 2002). This is reflected in their environments, as locally ULIRGs and QSOs reside in different environments, with ULIRGs generally lying in the field and QSOs lying in moderately rich environments on average, with a diverse range. We can compare the range of environments of our sample of HLIRGs to those of QSOs at comparable redshifts to see if this is also true at high redshift. The diverse range of environments seen in our sample of HLIRGs is qualitatively similar to the range seen in RLQs and RQQs, and our mean value for $B_{gg}$ is comparable to the mean galaxy-quasar correlation statistic, $B_{gq}$, for RLQs and RQQs at similar redshifts (Wold et al 2000, 2001). This is illustrated in Figure 4, where we plot clustering amplitudes vs. redshifts for our HLIRGs, together with a representative sample of clustering amplitudes for QSOs from the literature.

Figure 4. The clustering amplitude of F10026+4949 as a function of $H_0$ (for $\Lambda = 0.7$, $\Omega_0 = 0.3$). Error bars are the Poisson errors.
The environments of hyperluminous infrared galaxies at 0.44 < z < 1.55

We have presented deep wide-field K-band imaging of the fields of six Hyperluminous Infrared Galaxies, and quantified their environments using the $B_{gh}$-galaxy-HLIRG correlation amplitude, and the $N_{0.5}$ clustering statistic. We conclude the following:

1) The HLIRGs in our sample reside in a diverse range of environments, from the field to Abell 2 clusters. The mean clustering level of the sample, at $\langle B_{gh} \rangle = 190 \pm 45$, and the range of environments, are both significantly greater than those of the most luminous IR galaxies locally. We infer that, at high redshift, the galaxy evolution processes driving the evolution of IR-luminous galaxies are more diverse than at low redshift, and include mergers between gas-rich spirals in the field, but also include encounters in clusters and hierarchical buildup.

2) The mean clustering amplitude of the sample, and the range in environments, are comparable to those of QSOs at high redshift than do locally.

ACKNOWLEDGMENTS

We thank Carol Lonsdale and Margrethe Wold for illuminating discussion, and the referee for a very helpful report. This paper is based on observations made with the William Herschel Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. 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. DF was supported by NASA grant NAG 5-
3370 and by the Jet Propulsion Laboratory, California In-
stitute of Technology, under contract with NASA. MF and
AK were supported by PPARC.

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