The K-band Hubble diagram of sub-mm galaxies and hyperluminous galaxies

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ABSTRACT

We present the K-band Hubble diagrams (K − z relations) of sub-mm-selected galaxies and hyperluminous galaxies (HLIRGs). We report the discovery of a remarkably tight K − z relation of HLIRGs, indistinguishable from that of the most luminous radiogalaxies. Like radiogalaxies, the HLIRG K-z relation at z < 3 is consistent with a passively evolving ≃ 3L⊙ instantaneous starburst starting from a redshift of z ≃ 10. In contrast, many sub-mm selected galaxies are ≃ 2 magnitudes fainter, and the population has a much larger dispersion. We argue that dust obscuration and/or a larger mass range may be responsible for this scatter. The galaxies so far proved to be hyperluminous may have been biased towards higher AGN bolometric contributions than sub-mm-selected galaxies due to the 60µm selection of some, so the location on the K − z relation may be related to the presence of the most massive AGN. Alternatively, a particular host galaxy mass range may be responsible for both extreme star formation and the most massive active nuclei.

Key words: cosmology: observations - galaxies: evolution - galaxies: formation - galaxies: star-burst - infrared: galaxies - submillimetre

1 INTRODUCTION

Hyperluminous galaxies (HLIRGs, L > 10^{13}L⊙, as distinct from the less-luminous ultraluminous population with L = 10^{12−13}L⊙), were first identified from follow-ups of the IRAS mission (e.g. Kleinmann et al. 1988, Rowan-Robinson et al. 1991). Gravitational lensing was found to be responsible for some of the extreme luminosity of at least one HLIRG, IRAS F10214+4724 (Graham & Liu 1995, Serjeant et al. 1995, Broadhurst & Lehar 1995, Eisenhardt et al. 1996), but subsequent HST imaging of more HLIRGs showed no further lens candidates (Farrah et al. 2002a). The morphologies were found to be diverse, from interacting to quiescent. Although active nuclei have been found in all HLIRGs to date, the enormous gas and dust masses (e.g. Downes et al. 1993, Clements et al. 1992, Farrah et al. 2002b) are indicative of violent, possibly bolometrically-dominant, star formation. By fitting multi-wavelength photometry of HLIRGs, several authors have found comparable bolometric contributions from star formation and active nuclei in many HLIRGs. Hyperluminous galaxies appear to be a population of galaxies undergoing their major star formation episode (Rowan-Robinson 2000), but at an epoch in which AGN activity is also present (e.g. Rowan-Robinson 2000, Farrah et al. 2002b, Verma et al. 2002). The sub-mm detections of radiogalaxies (Archibald et al. 2001) and quasars (e.g. Priddey et al. 2003) further supported a link between violent star formation and AGN activity, though quasar-heated dust has also been raised as a possibility (Willott et al. 2002). In this paper we will present further evidence for a link between AGN activity and extreme star formation, using the K-band Hubble diagram.

The tight dispersion in the K-band Hubble diagram (K − z relation) of radiogalaxies has long been held to suggest a high formation epoch for radiogalaxies hosts (Lilly & Longair 1984). Redshifted emission line contributions (Eales & Rawlings 1993) complicate the interpretation at redshifts z > 2, but largely only for the most luminous radiogalaxies (e.g. Jarvis et al. 2001). The current consensus is that the tight ±0.5 magnitude dispersion in the radiogalaxy K − z relation persists at z > 2, and is still consistent with a passively evolving stellar population with a formation epochs at z > 2.5. There is also a weak correlation of K-band luminosity with radio luminosity at any epoch (e.g. Willott...
et al. 2003) which has been attributed to mutual correlations with central nuclear black hole masses. Furthermore, the host galaxies of radio-loud AGN tend to be restricted to a more luminous population than their radio-quiet counterparts (Dunlop et al. 2003a), suggesting that it is only the most massive ($>10^9 M_{\odot}$) nuclear black holes which give rise to radio-loud AGN. Finally, the similarity of the K-band morphologies of sub-mm-selected galaxies to those of high-$z$ radio galaxies, the high star formation rates in sub-mm galaxies (sufficient to assemble a giant elliptical in $\sim 10^9$ years), and the presence of radio-loud AGN in local ellipticals has suggested to some authors that both high-$z$ radio galaxies and sub-mm selected galaxies are the progenitors of the most massive spheroids (e.g. Dunlop 2002, Scott et al. 2002).

In this paper we report the discovery of a remarkably tight $K-z$ relation of HLIIRGs, and the surprising lack of a tight $K-z$ relation for coeval sub-mm-selected galaxies. Section 2 describes the compilation of $K$-band magnitudes, and the $K-z$ relations are presented in section 3. Section 4 places the results in the context of other high-$z$ populations, and discusses the physical implications and possible applications of this relation. Throughout this paper, “quasars” are taken to mean objects with broad ($\gtrsim 2000$ km s$^{-1}$) unpolarised emission lines, regardless of the presence or absence of a host galaxy in imaging data, and we assume $\Omega_M = 0.3$, $\Omega_L = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ = 100h km s$^{-1}$ Mpc$^{-1}$. In this cosmology, a minority of the hyperluminous galaxy compilation of Rowan-Robinson (2000) slip just below the hyperluminous threshold, and others attain hyperluminous status, but for consistency with previous works we restrict ourselves to this compilation. This choice does not affect the results in this paper.

## 2 METHOD

Table 1 lists the $K$ magnitudes for all non-quasar hyperluminous galaxies in the compilation of Rowan-Robinson (2000), except IRAS F14481+4454 and IRAS F14537+1950 for which no data is available. Several quasar HLIIRGs have optical host galaxy measurements (e.g. Farrah et al. 2002a), but we exclude these on the grounds that the $K$-band nuclear contribution will differ.

There are great difficulties with associating $14''$ resolution sub-mm blank-field survey galaxies with sources at other wavebands (e.g. Serjeant et al. 2003), especially given the non-Poissonian distribution of these and other populations (e.g. Almaini et al. 2003). Most claimed spectroscopic redshifts report spectroscopic evidence of star formation (e.g. Chapman et al. 2003), but one should note that there are precedents for identifications of sub-mm sources changing with the advent of new data (e.g. Dunlop et al. 2003b, Serjeant et al. 2003, Smail et al. 1999). The $K$ magnitudes of all published sub-mm galaxies with spectroscopic redshifts are listed in Table 2. We also include galaxies with $\geq 3$ band photometric redshifts, though the accuracy of these redshifts will depend on how closely the high-$z$ population resembles local templates (yet to be determined).

In addition to HLIIRGs and sub-mm galaxies, we have compiled comparative data from the literature on other, ostensibly related populations. We use the photometry and

### Table 1. K-band magnitudes for non-quasar hyperluminous galaxies of Rowan-Robinson (2000). Following Dunlop et al. (2003) we neglect the corrections between $K'$, $K_s$ and $K_L$ as these are smaller than the typical photometric errors ($\sim 0.1-0.2$ magnitudes). Bolometric luminosities are taken from Farrah et al. (2003), Farrah et al. (2002b) and Rowan-Robinson (2000). Notes: (1) corrected for $\times 1.3$ lens magnification factor; (2) corrected for emission line contribution and $\times 10$ magnification factor; (3) corrected for $\times 2.8$ lens magnification; (4) photometry from the data of Farrah et al. 2003 (note that those authors used slightly different photometric apertures); (5) photometry from 2MASS (Cutri et al. 2003); (6) photometry from Eisenhardt & Dickinson 1992; (7) photometry from Small, Ivison, Blain & Kneib 2002b; (8) photometry from Stanford et al. 2000; (9) photometry from Graham & Liu 1995; (10) photometry from Liu et al. 1996; (11) photometry from Graham et al. 1994

| Name                  | $z$   | log$_{10}$ $L_{bol}$ | $K$ | Aper | Notes |
|-----------------------|-------|----------------------|-----|------|-------|
| IRAS F00235+1024      | 0.58  | 13.15                | 17.19 | 3''  | (4)   |
| SMJ02399-0136         | 2.803 | 13.08                | 18.79 | 3''  | (1.7)  |
| 4C141.17              | 3.8   | 13.12                | 19.6  | 4''  | (11)  |
| IRAS 09104+4109       | 0.44  | 13.24                | 15.41 | 3''  | (4)   |
| IRAS F10214+4724      | 2.286 | 13.54                | 20.10 | 3''  | (2.9)  |
| IRAS F12514+1027      | 0.30  | 13.00                | 13.48 | 10'' | (5)   |
| SMJ14011-0252         | 2.55  | 13.18                | 18.71 | 3''  | (3.7)  |
| IRAS F15307+3252      | 0.93  | 13.50                | 16.59 | 2''  | (10)  |
| FFJ1614+3234          | 0.710 | 13.07                | 16.6  | 3''  | (8)   |

### Table 2. K-band magnitudes for sub-mm selected galaxies with spectroscopic redshifts or $\geq 3$ band photometric redshifts. Notes as table 1 and in addition: (12) from Smail et al. 2003 and Keel et al. 2002, and corrected for emission line contributions; (13) from Ivison et al. 2002; (14) Barger et al. 2000; (15) Fernandez-Soto et al. 1999; (16) Lilly et al. 1999; (17) from Dunlop et al. 2003, photometric aperture is small but source is not significantly more extended, and no account taken of lensing; (18) Gear et al. 2000; (19) Aretxaga et al. 2003; (20) Serjeant et al. 2003; (21) Chapman et al. 2003. Non-sub-mm selected galaxies (e.g. HR10) that are nevertheless detected in sub-mm photometry are excluded from this table.

| Name                  | $z$   | log$_{10}$ $L_{bol}$ | $K$ | Aper | Notes |
|-----------------------|-------|----------------------|-----|------|-------|
| SMJ00266+1708         | 2.0-5.0 | 23.45               | 3'' | (7,19) |
| SMJ09429+4658         | 2.1-4.5 | 20.15               | 3'' | (7,19) |
| LH850.1               | 2.0-3.0 | 19.8                | 4'' | (13,19) |
| LH850.3               | 1.2-3.5 | 18.86               | 4'' | (13,19) |
| LH850.8               | 2.4-5.2 | 18.82               | 4'' | (13,19) |
| HDF850.1              | 3.5-4.7 | 23.5                | 1'' | (17,19) |
| SMJ114099+0025        | 2.6-5.1 | 21.44               | 3'' | (7,19) |
| CUDISS14.1            | 2.0-4.6 | 19.55               | 4'' | (18,19) |
redshifts of non-quasar Chandra sources from the Hubble Deep Field North Chandra 1 megasecond catalogue of Barger et al. (2002), which is an improvement on the inhomogeneous compilations available to Willott et al. (2001). We also use the $K$-band photometry and spectral classifications of ultraluminous infrared galaxies of Kim et al. (2002) and Veilleux et al. (2002). Finally, we use the radiogalaxy photometry compilation in Willott et al. (2003). Because the 3CRR flux limit remains close to the radio $L_\ast$ ($L_\ast$(radio)), 3CRR radio galaxies lie at $\sim 3 - 4L_\ast$(radio) (Willott et al. 2003) at all redshifts. Note also that 3CRR sources are also the highest luminosity radio sources in the Hubble volume at $z < 2$.

3 RESULTS

Figure 1 shows the $K-$z relation of HLIRGs, compared to that of bright radio sources from the 3CRR survey (Laing et al. 1983) and 6CE survey (Eales et al. 1997). Willott et al. (2003) quotes a fit to the radiogalaxy $K - z$ relation of

$$K_{\text{pred}} = 17.37 + 4.53 \log_{10}(z) - 0.31(\log_{10}(z))^2.$$  

(1)

3CRR has dispersion around this relation of only $\pm 0.5$ magnitudes. The HLIRGs are statistically indistinguishable from the 3CRR radiogalaxies: a Kolmogorov-Smirnov test of the distributions of $K - K_{\text{pred}}$ of HLIRGs and 3CRR radio galaxies rejects the null hypothesis of same distributions at only 23% confidence.  

(We have excluded the hyperluminous radiogalaxy 4C41.17 from this test, though its magnitude is consistent with the $K - z$ relation of other HLIRGs table 1). Curiously however, the same cannot be said of sub-mm selected galaxies, also plotted in figure 1. Even assuming the $K$-band limits are obtained for these galaxies, the distributions are still dissimilar at 99.98% confidence. Figure 2 shows the HLIRG $K-z$ relation in the context of other potentially related populations. Note that the photometric redshifts of three sub-mm selected galaxies and at least 5 with spectroscopic redshifts place them securely away from the radiogalaxy locus.

Neither the sub-mm galaxies nor the HLIRG samples from Rowan-Robinson 2000 are spectroscopically complete. Could this selection bias cause our HLIRG $K-z$ relation? In a sample with a flux limit at two wavelengths, correlating the luminosity at one wavelength with that at the other is essentially a distance vs. distance correlation (e.g. Serjeant et al. 1998). However this cannot be the cause of our HLIRG $K-z$ relation because (a) the apparent $K$ magnitudes are not well-represented by a $K$ flux limit: the magnitude histogram of table 1 is more or less uniform from $K \sim 13$ to $K > 20$; (b) more importantly, the optical selection ($R$ or $B$) shows no greater evidence for clustering around a particular apparent magnitude. If Malmquist bias (distance vs. distance correlations) were responsible, we would expect more clustering around a particular apparent magnitude in the optical, compared to the $K$-band. As discussed in Rowan-Robinson 2000, there are probably optically-fainter HLIRGs still to be found in the IRAS database, and our results make very specific predictions for their $K$ magnitudes. However, if an as-yet-undiscovered selection effect results in the undiscovered HLIRGs having fainter $K$ magnitudes, this would change the results of this study.

In both figure 1 and 2 we overplot passive stellar evolution tracks of a $3L_\ast(K)$ galaxy (where $L_\ast(K)$ is the K-band $L_\ast$) for an instantaneous starburst at $z = 5$ starburst (long dash) and $z = 3$ starburst, from Willott et al. (2003). Also plotted are obscured starburst models of Takagi et al. (2003): age $t/\theta_0 = 2$, compactness $\Theta = 0.4$ (dash-dot) and $\Theta = 0.5$ (dash-dot-dot-dot). All models are for a $3L_\ast(K)$ galaxy.

4 DISCUSSION

The difference between the HLIRG and sub-mm galaxy $K-z$ relations is all the more puzzling given our discovery that some HLIRGs would have comparable sub-mm fluxes to sub-mm-selected galaxies, if redshifted to $z \sim 3$ (Farrah et al. 2002b), including two of the HLIRGs in the present paper. Given a template spectral energy distribution with

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1 Although this test is only asymptotically distribution-free, we verified the test in this case with a bootstrap analysis. We randomly selected 10 3CRR radio galaxies, and compared $K - K_{\text{pred}}$ for this subset against the remainder. By repeating this, we found that the confidence levels returned are well-represented by a uniform distribution on the interval $[0, 1]$ as required.
a sufficiently warm colour temperature, many of the sub-mm-selected galaxies could have bolometric luminosities approaching $10^{13}L_\odot$. Five of the ten HLIRGs in this paper were selected at 60µm, and two of the remainder were discovered by follow-ups of radiogalaxies, either of which may have introduced a bias towards high AGN bolometric contributions. If so, this would suggest that the position on the $K - z$ relation may be related to the presence of the most massive AGN. A prediction of this interpretation is that the multi-wavelength data on sub-mm galaxies from SIRTF (e.g. Lonsdale et al. 2003) should find an anticorrelation between $K - K_s$ magnitudes and the bolometric contributions in the mid-infrared.

Alternatively, the HLIRG $K - z$ relation may be intrinsic, rather than the product of a subtle AGN bias. All of the galaxies currently proved to be hyperluminous currently lie on a tight $K - z$ relation, including those selected in the sub-mm. Also, radiative transfer models of the Rowan-Robinson (2000) HLIRGs do not find the AGN to be bolometrically dominant in all cases (e.g. Verma et al. 2002, Farrah et al. 2002b). There is no prima facie reason to suppose that HLIRGs should necessarily follow the radiogalaxy $K - z$ relation. For example, the obscured high-redshift AGN detected by Chandra are not found with similar $K$ magnitudes to radiogalaxies (or HLIRGs, figure 2), which Willott et al. (2001) argued was due to the Chandra sources hosting smaller mass nuclear black holes. However, the relative number densities of radiogalaxies and HLIRGs lend plausibility to a physical link between the populations, or at least a common progenitor. Rowan-Robinson (2000) lists 16 HLIRGs with $z \leq 1$, implying a lower limit to the $z \leq 1$ HLIRG number density of $\geq 3 \times 10^{-10}h^3\text{Mpc}^{-3}$, and also estimates that only $\sim 10 - 20\%$ of HLIRGs have been identified to date. These number densities are comparable to the $z \leq 1$ number density of 3CRR radio galaxies ($1.1 \times 10^{-2}h^3\text{Mpc}^{-3}$) and significant compared to $z \leq 1$ 3CRR active galaxies as a whole ($2.5 \times 10^{-5}h^3\text{Mpc}^{-3}$). Notably, both HLIRGs and 3CRR are the most luminous in the Hubble volume of their class.

This does not necessarily imply that radiogalaxies and HLIRGs must be the most massive galactic systems in the Hubble volume. Huang et al. (2003) measured the space density of $10L_\odot(K)$ galaxies to be $2.1 \times 10^{-9}h^3\text{Mpc}^{-3}$ at $z < 0.4$. These galaxies are 2.5 magnitudes brighter than the HLIRG and radiogalaxy host galaxies, and $\sim 10\times$ more numerous than radio-loud AGN. However, the space density of $>10L_\odot(K)$ galaxies has not been determined at higher redshifts.

There is evidence in figure 3 that infrared luminosity scales with host luminosity, in a manner reminiscent of the trend of host luminosity with radio lobe luminosity in radiogalaxies (Willott et al. 2003). The difference in the mean $K - K_s$ for the $1 - 3 \times 10^{12}L_\odot$ and $>10^{14}L_\odot$ bins is significant at 99.6% confidence using Student’s T statistic, though the objects in these bins span different redshifts, so differential evolution may also be a factor (e.g. Serjeant et al. 1998). Samples of infrared-luminous galaxies spanning a narrow range in redshift, but a wide range in luminosity, are needed to test this relationship definitively. Such samples may become available with the advent of SIRTF.

If radiogalaxy and HLIRG activity is both short lived and rare (in the sense that a $5L_\odot(K)$ galaxy has a low probability of ever hosting a radiogalaxy or HLIRG), then the lack of $>10L_\odot(K)$ HLIRGs might be explained by the finite size of the volume surveyed so far for HLIRGs. If we assume that $K$-band galaxies in the range $0.5 - 5L_\odot(K)$ are the hosts of short-lived HLIRG activity with $10^{13-14}L_\odot$, and we interpolate from the $K$-band luminosity function (Huang et al. 2003) keeping the HLIRG duty cycle constant, then the space density of $10^{14-15}L_\odot$ galaxies should be around a factor of $\sim 1000$ lower. This is, of course, only a toy model: the $K$-band luminosity function is unlikely to keep the same shape at all redshifts, the luminosities may not scale with the host galaxy masses, and the duty cycle assumptions may be ill-founded, but this does raise the interesting question of the existence of still more extreme populations of infrared galaxies. Source count models differ widely in their predictions at these luminosities (Pearson 2001, Rowan-Robinson 2001). Whether such systems do in fact exist may be testable with the next generation of sub-mm/mm-wave survey facilities, such as SCUBA-2 (Holland et al. 2003) or the LMT (Baars et al. 1998).

In short, there are plausible precedents for abundant populations of galaxies with evidence of dust-enshrouded AGN, extreme luminosities and/or large stellar masses, which are many times more luminous in $K$, or many times less luminous, than HLIRGs. The fact that these populations do not host HLIRG activity suggests that the similarity of the HLIRG and radiogalaxy $K - z$ relations is due to a direct physical link between the two phenomena, such as an evolutionary connection, or a common progenitor population. Alternatively, the position of HLIRGs on the $K - z$ relation may be solely related to the presence of the most massive AGN (see above), for which a key test is whether...
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**Figure 3.** K-band luminosity relative to $L_\star$ ($z = 10$ starburst model), plotted against bolometric luminosity. HLIRGs: filled circles; ultraluminous galaxies: crosses. Also plotted are the mean values in binned luminosity ranges (horizontal lines). The standard deviation is $\pm 0.6$ magnitudes in each bin, and the errors on the means are plotted as vertical lines. Note that for our cosmology, some of the Rowan-Robinson (2000) compilation just below the HLIRG threshold, and one of the ultraluminous galaxies becomes HLIRGs. For consistency with previous work, we restrict our HLIRGs to the Rowan-Robinson (2000) compilation, but as can be seen from this figure this choice does not affect our conclusions.

The SIRTF detects hyperluminous AGN activity in sub-mm selected galaxies.

Surprisingly, sub-mm galaxies have a very different distribution in the $K-z$ plane. This is contrary to the result of Dunlop (2002) due to the subsequent increase in (ostensibly) reliable spectroscopic redshifts. The spectroscopic redshift of ELAIS N2850.1 is anomalous compared to its radio:sub-mm ratio, which led Chapman et al. (2002) to suggest that the system may be lensed. Placing the system at higher redshift may well restore ELAIS N2850.1 to closer to the locus of the radiogalaxy $K-z$ relation. Nevertheless, several photometric or spectroscopic redshifts place sub-mm galaxies away from the radiogalaxy $K-z$ relation. Plausibly, these may represent separate populations; there is no reason to suppose that sub-mm selected galaxies represent a single homogeneous population of objects (e.g. Dannerbauer et al. 2002), as with Extremely Red Objects (e.g. Smail et al. 2002a).

One possibility is that some sub-mm galaxies are less massive systems; another is that not all of them are the progenitors of the most massive ellipticals (Efstathiou & Rowan-Robinson 2003, Kaviani et al. 2003) but rather are cool cirrus-dominated objects. Alternatively, some sub-mm galaxies may be heavily extinguished even in the observed-frame $K$-band. Such an interpretation is physically plausible: figures 1 and 2 show the predictions of such a model from Takagi et al. 2003.

The HLIRG $K-z$ relation could be used to estimate redshifts of HLIRG candidates, as was the early practice for radiogalaxies (e.g. Dunlop & Peacock 1990). Based on the 3CRR radiogalaxy $K-z$ relation, the $K$ magnitude is sufficient to determine the redshift of HLIRGs to better than $\pm 10\%$ in $(1+z)$ at all redshifts, provided the systems are indeed hyperluminous and are not quasars. Regarding the hyperluminous quasars in Farrah et al. (2003), we can predict that the hyperluminous quasar LBQ5 1220+0939 should be dominated by the host galaxy flux in $K$, while the hyperluminous quasar IRAS F10119+4129 should be dominated by the nuclear component in $K$. The remaining cases in Farrah et al. (2003) should be intermediate between these two cases.

Only two of the known non-quasar HLIRGs lack $K$-band photometry, so further tests of the HLIRG $K-z$ relation using HLIRGs discovered to date must rely on subarcsecond near-infrared imaging of hyperluminous quasar hosts. Alternatively, both SIRTF and ASTRO-F will have sensitive $L$ and $M$-band cameras, which can further reduce the contribution from the active nucleus by sampling closer to the rest-frame $K$-band.

5 ACKNOWLEDGEMENTS

We would like to thank Chris Willott for kindly supplying the stellar evolution curves, and the anonymous referee for very helpful suggestions, including the possibility that an AGN bias in the Rowan-Robinson (2000) sample may be related to their position on the $K-z$ relation. This research was supported by PPARC grant PPA/G/0/2001/00116, and Nuffield Foundation grant NAL/00529/G. 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 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.

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