ISO PHOTOMETRY OF HYPERLUMINOUS INFRARED GALAXIES: IMPLICATIONS FOR THE ORIGIN OF THEIR EXTREME LUMINOSITIES

Aprajita Verma[1], Michael Rowan-Robinson[2], Richard McMahon[3], and Andreas Efstathiou[4]

[1]Max-Planck Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany.
[2]Astrophysics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BZ, England.
[3]Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England.
[4]Department of Computer Science & Engineering, Cyprus College, 6 Diogenous Street, P O Box 22006, 1516 Nicosia, Cyprus.

ABSTRACT

We present 7-180μm photometry of a sample of hyperluminous infrared galaxies (HyLIGs) obtained with the photometer and camera mounted on the *Infrared Space Observatory* (ISO). We have used state-of-the-art' radiative transfer models of obscured starbursts and dusty tori to model their broadband spectral energy distributions (SEDs). We find that IRAS F00235+1024, IRAS F14218+3845 and IRAS F15307+3252 require a combination of starburst and AGN components to explain their mid to far-infrared emission, while for TXS0052+471 a dust torus model alone is sufficient. For IRAS F00235+1024 and IRAS F14218+3845 the starburst component is the predominant contributor whereas for IRAS F15307+3252 the dust torus component dominates. The implied star formation rates (SFR) estimated from the starburst infrared luminosities are $dM_{*,all}/dt > 1000 M_{\odot} yr^{-1} h_{50}^{-2}$ and are amongst the highest SFRs estimated to date. We also demonstrate that the well-known radio-FIR correlation observed for extragalactic sources extends into both higher radio and infrared power than previously investigated. The relation for HyLIGs has a mean q value of 1.94. The results of this study imply that better sampling of the IR SEDs of HyLIGs may reveal that **both** AGN and starburst components are required to explain their emission from the NIR to the sub-millimetre.

Key words: infrared: galaxies - radio continuum: galaxies - galaxies: starburst - galaxies: Seyfert

1. INTRODUCTION

Hyperluminous infrared galaxies constitute the most luminous ($L_{IR} > 10^{13} L_{\odot} h_{65}^{-2}$) fraction of the extragalactic population characterised by predominant emission in the infrared (IR) wavelength range. These dusty objects are often thought to be the local analogues of the high-redshift sources being discovered in recent sub-mm surveys (Hughes et al. 1998, Ivison et al. 1998, Scott et al. 2002) and possibly the unresolved population that contributes to the IR background (Comastri et al. 1995, Fabian et al. 1998). The nature of the power source fueling their extreme luminosities therefore has implications for the origin of the IR/sub-mm backgrounds and galaxy evolution scenarios. Whether their powerful emission is due to thermal re-radiation by dust of UV/optical photons emanating from obscured compact starbursts or deeply dust enshrouded AGN remains a controversial issue as many luminous IR galaxies often display both starburst and AGN signatures. This is the so-called 'starburst-AGN controversy' that has been well studied, and to an extent elucidated, for ultraluminous IR galaxies (ULIGs) using the photometric and spectroscopic results of ISO (e.g. Genzel et al. 1998, Klaas et al. 2001).

For the faintest and most distant members of this population, investigating the underlying power source becomes even more difficult due to poorly sampled IR SEDs and the inability to obtain good quality spectroscopic measurements. Therefore, with the aim to ascertain the nature of the obscured power source, we obtained mid-far IR photometry of a sample of HyLIGs using the photometer (PHT) and camera (CAM) mounted on ISO. By combining these data with existing optical, IRAS and radio data we constructed SEDs which we interpreted by fitting state-of-the-art' radiative transfer models of obscured starbursts and dusty tori. The deconvolution of the SED into AGN and starburst components allowed us to determine likely fueling fractions to the total IR power.

2. SAMPLE & DATA REDUCTION

We present SEDs of four HyLIGs from an originally proposed sample of 15, limited only by observing constraints. Observations were carried out using PHOT at FIR wavelengths and imaged in the MIR with CAM.

CAM images at 6.75 and 15μm were taken in the photometric imaging CAM01 mode. Reduction was carried out using the CAM Interactive Analysis software[1] (CIA) with dark current, flat-fielding, deglitching and stabilisation corrections applied.

PHOT observations were taken using the observation modes PHT03 at 25μm and PHT22 at 60, 90 and 180μm. These filters were chosen to span the greatest wavelength range and complement the existing IRAS data. The data were reduced using PHOT Interactive Analysis (PIA) Software (version 9.1)[2] from the edited raw data products. PHT-P observations at 25μm were reduced using the standard procedure but in the absence of a complementary background measurement,

[1] The CAM data presented in this paper was analysed using 'CIA', a joint development by the ESA Astrophysics Division and the CAM Consortium. The CAM consortium is led by the CAM PI, C. Cesarsky.

[2] PIA is a joint development by the ESA Astrophysics division and the PHOT Consortium led by MPIA, Heidelberg. Contributing PHOT Consortium institutes are DIAS, RAL, AIP, MPIK and MPIA.

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were used as an upper limit. The remaining long wavelength data was reduced using tools specifically developed for reducing chopped data. [See Verma et al. (2002) for details.] We assessed the reliability of the long wavelength detections by determining the level of cirrus confusion noise on each measurement.

3. ANALYSIS

3.1. SED Fitting

The resulting SEDs were compared to combinations of radiative transfer models of inclined dusty tori (Efstathiou, Hough & Young, 1995, EHY95) and state of the art starburst models (Efstathiou, Rowan-Robinson & Siebenmorgen 2000, ERS00). The contributions of both components were allowed to freely vary. Other parameters that were allowed to vary were orientation of the torus, starburst age and starburst optical depth. It is important to note that we were by no means sampling the full parameter space of starburst or AGN models since both are defined with discrete parameters. The number of free parameters we used was restricted by the sampling of the SED. This enabled the quality of the combined fit to be assessed using the reduced chi squared estimator. For the lowest chi-squared values we accepted all fits with the minimum chi-squared and one plus the minimum as reasonable fits. The degeneracy of combinations within this chi-squared range was investigated to determine the most likely starburst:torus contributions to the total power.

An accurate total luminosity was determined by integrating over the best fitting combined model. Thus errors incurred due to the approximations used to determine this quantity from IRAS fluxes were eliminated. In addition, the dust mass involved was directly obtained from the starburst models. The decoupling of the SED into starburst and AGN components, meant that SFRs were determined solely from the starburst luminosity.

3.2. FSC 00235+1024

The mean combination of the best fitting models to the SED of this source is 64%:36% starbursts:torus. Without a strong MIR constraint we cannot rule out the possibility of a stronger AGN component. However the current modelling shows that stronger torus components greatly over-predict the MIR emission measured by CAM. Both the dominance of the starburst contribution and the orientation of the dusty torus are consistent with soft X-ray upper limits and its narrow-line classification from optical spectra. This z=0.59 source has a total IR luminosity of $L_{IR} = 2.29 \times 10^{13} L_{\odot}$ with 65% originating from the starburst model giving a dust mass $M_D = 1.2 \times 10^9 M_{\odot}$.

3.3. TXS 0052+471

The SED of TXS0052+471 is best fit by a torus model alone. Within the range of best-fitting models, a low (<4%) starburst contribution was plausible but this combination passed through the sub-mm upper limits, and therefore a null starburst contribution was preferred. This source was discovered in a correlation of the IRAS Faint Source Reject Catalogue (FSR) with the TEXAS radio survey and is the only radio-loud object within our sample. The ISO detections provide evidence that the FSR source is real. At a redshift of 1.94, this quasar is one of the most luminous HyLIGs, with $L_{IR} = 1.1 \times 10^{14} L_{\odot}$.

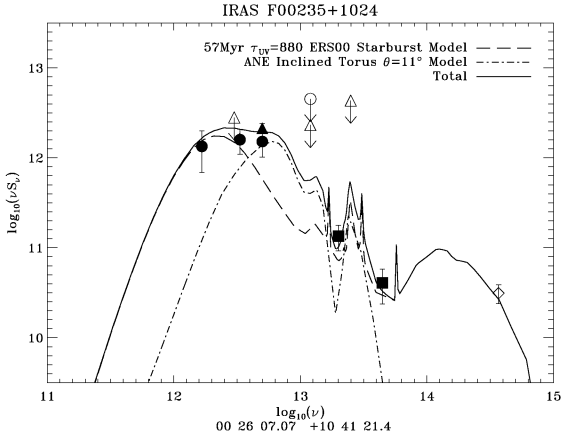

Figure 1. Best-fitting model for FSC00235. Detections are plotted as filled symbols and upper limits as open symbols with arrows plotted directly below: PHT - circles, CAM - squares and IRAS - traingles. Additional data obtained from literature are plotted on the SEDs as open diamonds (with arrows below if upper limits).

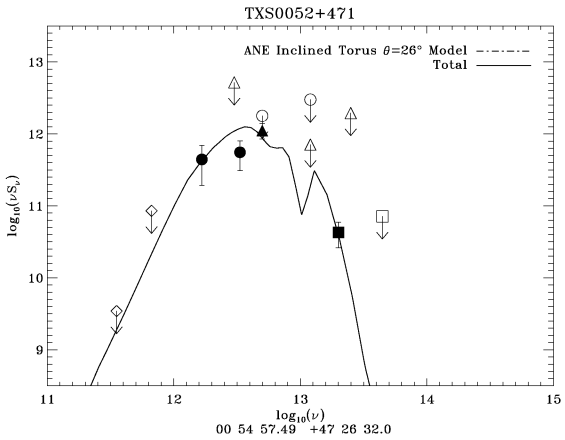

Figure 2. Best-fitting model for TXS0052+471. Key as Fig. 1.

3.4. FSC 14218+3845

The ISO photometry does not confirm the IRAS fluxes which are now believed to be contaminated by cirrus flux. By combining the PHOT and CAM data we were able to identify IR emission arising from the quasar previously associated with the IRAS source at z=1.21. Despite a drop in flux of over a factor of 10 this source remains a bona fide HyLIG with $L_{IR} =$

$2.27 \times 10^{13} L_{\odot}$. The fitting analysis showed a combined model at a level of 75-85%:15-25% starburst:torus was preferred to explain the SED over a range of torus only models or any other starburst AGN combination. The orientation of the torus ($59.5^{\rm deg}$) is consistent with the detection of broad lines in the optical spectrum.

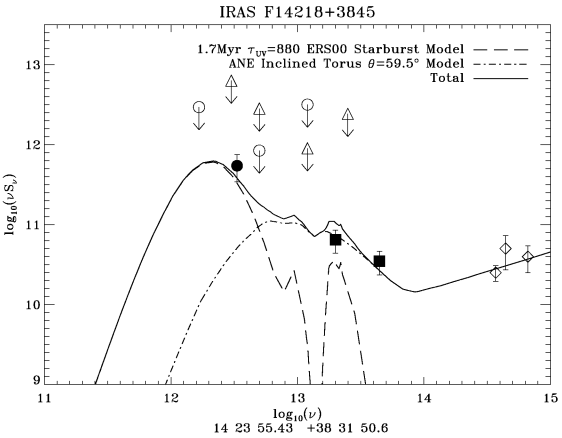

Figure 3. Best-fitting model for F14218+3845. Key as Fig. 1.

3.5. FSC 15307+3252

We combined our data with photometry from a CAM-CVF spectrum (Aussel et al. 1998) enabling the use of an extended set of starburst and torus models. The non-detection of PAH features in the MIR and the strong FIR detections dictate strong AGN and starburst components respectively. The majority of best-fitting combined models are predominantly torus fueled. The model shown represents one of the best fit models with 70%:30% torus to starburst contribution. The orientation of the torus model is consistent with 3 observational clues: Seyfert 2 classification, detection of a broad MgII line in the polarised spectrum and soft X-ray upper limits. The non-detection of CO(J = 4 → 3) by Yun & Scoville (1998) favours low gas mass and therefore a low starburst component. The dust mass estimated from the starburst model is consistent with limit on the gas mass.

4. THE FIR-RADIO CORRELATION

Here we demonstrate that the well known radio-IR correlation for starbursts and ULIGs extends to higher power for HyLIGs. Radio detections from the NVSS catalogue (Condon et al. 1998) were sought for all HyLIGs catalogued in Rowan-Robinson (2000, RR00). Excluding the TEXAS radio-loud quasars (those clustered around TXS 0052+471) we see that the HyLIGs follow the broad correlation seen in the Condon et al. (1991, C91) and Stanford et al. (2000, S00) data for LIGs and ULIGs. The mean q-value [used to parameterise the FIR-radio correlation $q = log_{10}(S_{60\mu m}/S_{1.41GHz})$] for the NVSS detected HyLIGs

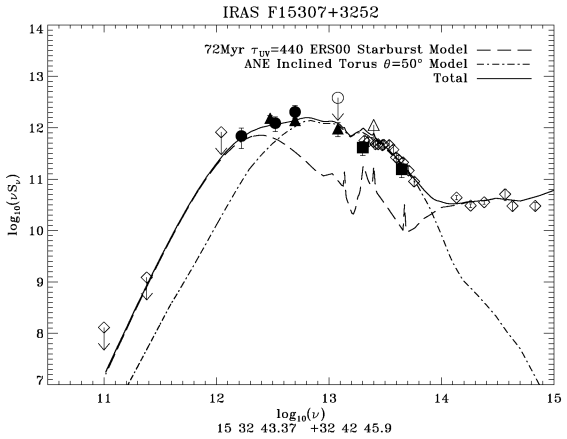

Figure 4. Best-fitting model for F15307+3252. Key as Fig. 1.

is 1.66. This is lower than the typical value determined for starburst galaxies and radio-quiet quasars ($\sim$ 2.3). However, if the sample is split we find that (a) the radio-loud TEXAS HyLIGs have $< q >= 0.89$ which is consistent with the value for radio-loud quasars ($0 < q < 1$) (b) for the remaining HyLIGs $< q >= 1.94$ which almost lies within the typical range for starburst and radio-quiet quasars (2-2.6) but is much lower than the mean derived for LIGs and ULIGs ($q = 2.34$ and $q = 2.28$ from C91 and S00, respectively). However, the NVSS undetected HyLIGs have radio fluxes *below* 2.7mJy (the completeness limits of the NVSS) and their inclusion will cause the value of $< q >$ to be higher.

5. SUMMARY

ISO measurements of HyLIGs have been performed to ascertain the nature of these extreme infrared objects.

a) Four objects, with faint IRAS detections, have been confirmed to be real infrared sources and constitute some of the most luminous sources in the Universe
($L_{IR} > 1 \times 10^{13.35} h_{50}^{-2} L_{\odot}$).

b) The broad-band SEDs of these objects have been compared to starburst and Seyfert models. The IR emission of FSC00235 and FSC14218 are predominantly starburst fueled whereas predominant AGN fueling is seen for TXS0052 and FSC15307.

c) The radio-IR luminosity correlation has been verified to continue to previously un-investigated radio and infrared luminosity powers. The mean q value for the radio-quiet sources (1.94) is lower than that previously determined for ULIGs (2.34) and indicates higher radio luminosities for HyLIGs.

With so few sources it is difficult to extrapolate our findings to the entire population. Nevertheless, we can state that **ALL of our sources require contributions from an AGN component to completely explain their IR SEDs**. This result in a sample of galaxies limited only by observing constraints suggests that obscured AGN and the hyperluminous phenomenon are linked. We therefore conclude from the results of this study, coupled with the multi-wavelength data available to date, that it

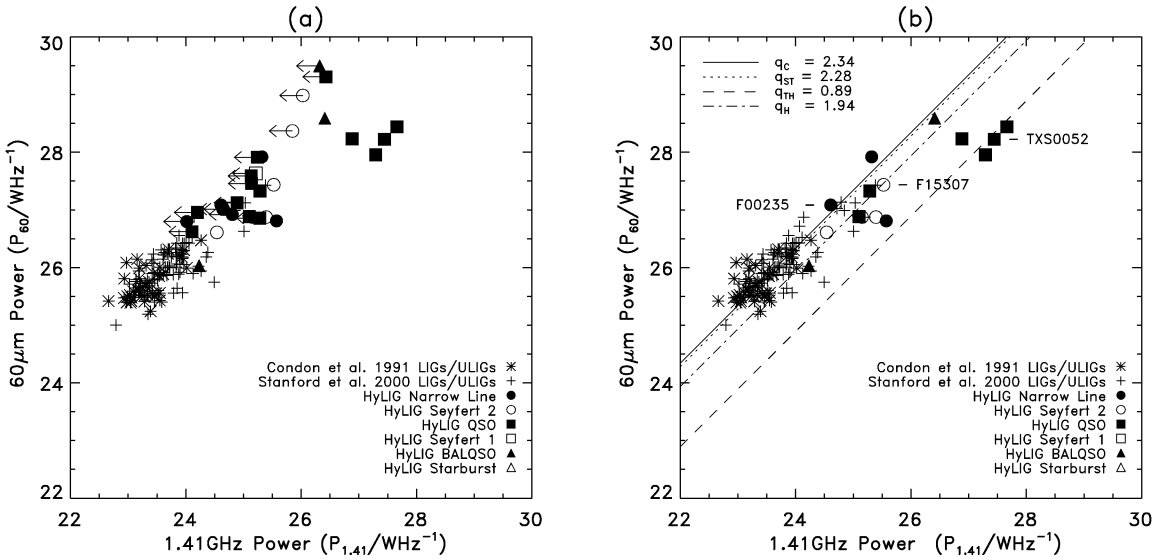

Figure 5. The figures above show the correlation between the calculated 60μm and 1.41GHz power. The plot includes LIGs and ULIGs from the samples of C91 and S00. It also contains data for the entire ISO-HyLIG sample and from the compilation of known HyLIGs from RR00. Plot (a) includes all detected sources and a radio upper limit of 2.7 mJy is shown for sources undetected within the NVSS survey. Plot (b) includes only those HyLIGs with confirmed NVSS counterparts. Overplotted are lines representing the median q *values for the C91 sample (q_C), the S00 sample (q_{ST}), the four radio-loud hyperluminous TEXAS sources (q_{TH}) and the remaining hyperluminous sources (q_H).*

is likely that HyLIGs contain AGN which contribute to the infrared emission. However, they are not energetically dominant in all HyLIGs.

In a complementary programme, we have performed similar analysis on three large and complete samples of ULIGs. We find that ∼70% of the samples require both AGN and starburst components to completely explain their NIR-FIR emission. In approximately one third of these cases, the torus model is the predominant contributor. Combining the results of the ULIG and HyLIG samples imply the following:

(i) Combined SED fits imply that a high fraction (∼70%) of U/HyLIGs present evidence of coeval AGN and starburst activity.

(ii) The fraction of bolometrically dominant AGN increases with luminosity (15-20% for ULIGs [Genzel et al. 1998, Verma et al. in prep] and 50% for HyLIGs [Verma et al. 2002]) which supports the findings of previous studies (e.g. Shier et al. 1996, RR00).

(iii) If HyLIGs are the local counterparts to the high-z sub-mm sources, we may find a substantial fraction to have significant power contributions from obscured AGN.

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