Galaxy Colours in the AKARI Deep SEP Survey

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Abstract

We investigate the segregation of the extragalactic population via colour criteria to produce an efficient and inexpensive methodology to select specific source populations as a function of far-infrared flux. Combining galaxy evolution scenarios and a detailed spectral library of galaxies, we produce simulated catalogues incorporating segregation of the extragalactic population into component types (Normal, star-forming, AGN) via color cuts. As a practical application we apply our criteria to the deepest survey to be undertaken in the far-infrared with the AKARI (formerly ASTRO-F) satellite. Using the far-infrared wavebands of the Far-Infrared Surveyor (FIS, one of the focal-plane instruments on AKARI) we successfully segregate the normal, starburst and ULIRG populations. We also show that with additional MIR imaging from AKARI's Infrared Camera (IRC), significant contamination and/or degeneracy can be further decreased and show a particular example of the separation of cool normal galaxies and cold ULIRG sources. We conclude that our criteria provide an efficient means of selecting source populations (including rare luminous objects) and produce colour-segregated source counts without the requirement of time intensive ground-based follow up to differentiate between the general galaxy population.

Key words: Space-based infrared telescopes, Far infrared, Galaxy evolution, Extragalactic surveys

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1 Introduction

Fueled by rapid advances in detector technology, enabling fast and accurate mapping of large areas of the sky, extragalactic astrophysics is enjoying a golden age where astronomers have become spoiled for choice with the enormous statistical survey data sets available probing out to cosmologically significant distances such as the optical Sloan Digital Sky Survey (SDSS) covering one quarter of the sky (Adelman-McCarthy et al., 2006), the near infrared UKIRT Infrared Deep Sky Survey (UKIDSS, 4000 square degrees (Lawrence et al., 2006)) and the Spitzer Wide-area Infrared Extragalactic Survey (SWIRE, Lonsdale et al., 2004). The most basic tool for the study of cosmological galaxy evolution is the monochromatic (single band) number count of extragalactic sources. However aside from source counts and clustering analysis of large scale structure, deeper investigation into the extragalactic population and cosmological evolution will inevitably require multi-wavelength analysis and hence galaxy colours. Ultimately we would like to define the extragalactic zoo species by species and derive their corresponding distances to determine the star-formation rate and sequence of structure formation in the Universe. However such studies often involve extremely time intensive follow up campaigns with either deep imaging or spectroscopy. As an intermediate step, galaxy colours have been frequently used to gain a cheap yet effective insight into galaxy populations and rough distances at a fraction of the cost of large scale follow-up campaigns. Such colour analysis has been extremely effective in selecting and segregating populations of sources in the near-infrared, optical and ultra-violet wavebands (e.g. the Lyman break population (Steidel et al., 1996; Madau et al., 1996), ERO & BzK sources (Elston et al., 1988; Cimatti et al., 2002)). At infrared wavelengths astronomers have often had to work with fewer bands and less well behaved detectors, yet the colour criteria has also been applied with great success in the mid-far-infrared with the pioneering IRAS mission’s all-sky survey (Soifer et al., 1987). Using simple colour criteria, Rowan-Robinson & Crawford (1989), Helou (1986) created a parameterization of the extragalactic population based on the IRAS infrared colours in four bands. Within this framework, a normal galaxy component was defined by cool 100µm/60µm colours, a starburst component defined by warm 100µm/60µm colours extending to an ultraluminous component at higher infrared luminosities and an AGN

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component was defined by high 25µm/60µm colours due to strong emission from the mid-infrared dust torus. Two decades after the IRAS all-sky survey, the Japanese AKARI mission (launched successfully on February 21st 2006, formerly known as ASTRO-F) will perform a new All-Sky Survey in 4 far-infrared and 2 mid-infrared bands to much improved sensitivity, higher spatial resolution and wider wavelength coverage (Shibai, 2004; Pearson et al., 2004; Pearson, Shibai et al., 2007). AKARI is equipped with a 68.5 cm cooled telescope (Kaneda et al., 2005) and two focal plane instruments, the Far-Infrared Surveyor (FIS) and the InfraRed Camera (IRC). The FIS has two 2-dimensional detector arrays and observes in four far-infrared bands between 50 and 180 µm (centred on N60 (65µm), WIDE-S (90µm), WIDE-L (140µm), N160 (160µm), Kawada et al. (2004)). The IRC consists of three cameras covering 1.7–26 µm in 9 bands (N2 (2.4µm), N3 (3.2µm), N4 (4.1µm), S7 (7µm), S9W (9µm), S11 (11µm), L15 (15µm), L18W (18µm), L24 (24µm)) with fields of view of approximately 10' × 10' (Onaka et al., 2004). Both the FIS and IRC instruments also have capabilities for spectroscopy. In addition to the All-Sky Survey, AKARI will also perform deep pointed surveys over areas of one to ten square degrees at the North (NEP) and South (SEP) Ecliptic Poles (Matsuhara et al., 2006). These major legacy surveys are expected to yield hundreds of thousands of sources and thus require a major data reduction effort. As a precursor to these surveys, the aim of this work is to investigate the feasibility of colour segregation of the infrared populations with the minimum peripheral data and effort as possible in a similar manner to the IRAS survey. Our colour segregation criteria will have merits not only for the AKARI data sets but also for similar large data sets expected from the Spitzer & Herschel missions. In this paper we concentrate on the deep region selected for the AKARI SEP survey while a more detailed investigation of our methods and their applications will be reported in Pearson & Jeong (2007).

2 Phenomenological Model for Colour Segregations

2.1 Spectral Energy Distribution Library

To model the colours of the extragalactic populations we have gathered a selection of spectral energy distribution (SED) templates for various galaxy populations from four large readily available contemporary spectral libraries. Computational constraints from our simulations restricts us from utilizing entire sets of thousands of SEDs so rather we have selected a moderate sub-sample which spans the entire range of spectral properties of the libraries. The selected sets of SEDs specifically model the quiescent normal galaxy population, the starburst population (increasing in luminosity: starburst, luminous infrared galaxies (LIRG), ultra-luminous infrared galaxies (ULIRG)) and the AGN popula-
tion. To model the quiescent normal galaxy population we have selected spectral templates from the libraries described in Efstathiou & Rowan-Robinson (2003) and Dale et al. (2001). The models of Efstathiou & Rowan-Robinson (2003) provide good fits to the IRAS, ISO and Spitzer selected samples of the cool, quiescent galaxy population (Rowan-Robinson et al., 2004, 2005) as well as the cold component of the sub-millimetre source population (Efstathiou & Rowan-Robinson, 2003) and the galaxy source counts from sub-millimetre to near-infrared wavelengths (Pearson, 2001, 2007). The model templates of Dale et al. have been shown to provide good fits to local normal galaxies from both ISO and more recently Spitzer selected samples (Dale et al., 2001, 2005), high-z Spitzer sources (Appleton et al., 2004) and the ISO & Spitzer mid-infrared source counts (Pearson, 2005). The starburst, LIRG, ULIRG population SEDs are taken from the radiative transfer models of Efstathiou, Rowan-Robinson & Siebenmorgen (2000) and Takagi et al. (2003a,b). The starburst models of Efstathiou have provided good fits to a wide variety of individual objects from starburst (e.g. M82), LIRG (e.g.NGC6090, IRAS1445-4343) to ULIRG sources (e.g. ARP220, MK231), (Efstathiou, Rowan-Robinson & Siebenmorgen, 2000, Efstathiou & Siebenmorgen, 2005) and also the recent results from the Spitzer SWIRE survey (Rowan-Robinson et al., 2005). The models of Takagi et al. provide good fits to the SEDs of dusty sub-millimetre galaxies (Takagi et al., 2004). The AGN population is modelled on the recent SED library of Siebenmorgen et al. (2004), Siebenmorgen & Efstathiou (2005). The SED libraries provide models for both Type 1 and Type 2 AGN by the consideration of tapered disc geometries. The selected SEDs are shown in Figure 1. Further details of the model selection are provided in Pearson & Jeong (2007).

2.2 Simulated Catalogues and Galaxy Colours

To estimate the expected fluxes and corresponding colours in the AKARI bands we use the contemporary galaxy evolution model of Pearson (2007). This model uses a backward evolution process based on the the IRAS all-sky PSCz multi-component luminosity function defined at 60µm comprising of cool normal quiescent galaxies, and a warmer component defined by infrared luminosity as $L_{IR} < 10^{11}L_\odot$ starburst galaxies, $L_{IR} > 10^{11}L_\odot$ LIRG sources, $L_{IR} > 10^{12}L_\odot$ ULIRG sources and AGN. This model fits the observed source counts from 2-1200µm from the IRAS, ISO, Spitzer missions and the SCUBA/JCMT, MAMBO/IRAM instruments (Berin et al., 1997, Puget et al., 1999, Dole et al., 2004, Fazio et al. 2004, Aussel et al., 1999, Serjeant et al., 2000, Papovich et al., 2004, Blain et al., 2002, Greve et al., 2004). Our source colour information is simulated by passing a catalogue of point sources through the instrument simulator of Jeong et al. (2004). An input catalogue is constructed for the 5 broad galaxy types outlined above within the framework of Pearson (2007). The catalogue is constructed as a function
of increasing redshift in incremental redshift bins. For each redshift bin, the theoretical number-redshift distribution from the model is used to randomly select the appropriate number of galaxies at that redshift and a corresponding luminosity by sampling the input luminosity function. Each source from the catalogue is assigned a SED from the library depending on the galaxy type and the expected flux for each source from the corresponding SED at the desired wavelength and redshift is calculated and convolved with the appropriate filter response function. A one sigma variation in the SED flux (i.e. for a given source in the catalogue the assigned flux at a given wavelength is selected randomly between ±1σ of the original SED template flux) is also included at this stage to allow for a wider range of output fluxes for a limited number of input SEDs. Note that although the instrument simulator is optimized for the AKARI mission (Jeong et al., 2004), it is a simple matter to extend the simulator to encompass the characteristics of the infrared pass-bands of other space missions (e.g. Spitzer, Herschel, etc., see Pearson & Jeong (2007)). The final output from the simulator is a catalogue of sources with associated SED, and filter band convolved fluxes at a set of desired wavelengths.

3 Predicted Colours of the Extragalactic Population in the AKARI SEP survey

In this work, the simulated source catalogue is used to investigate the deep AKARI SEP survey. The AKARI SEP survey is a guaranteed time AKARI Mission Program (MP). The current projected area spans ~8 square degrees in a low cirrus brightness region centred at R.A. = 4h44m00s, Dec = -53deg 20′00′′0 (J2000) where the cirrus brightness is spectacularly low < B_{100} > ∼ 0.2 MJy/sr (Schlegel, Finkbeiner & Davis, 1998). This survey is estimated to reach the source confusion limit in the far-infrared FIS wide bands and will be the deepest far-infrared image of the Universe to date (note that Jeong et al. (2006) predict confusion limits of ∼10mJy & 60mJy in the FIS 90µm and 140µm bands respectively based on the source confusion criterion of 20 beams per source). Shallow mid-infrared data will also be available over the entire area, along with deep optical R-band imaging to 25th magnitude. In addition, an area of approximately 1 square degree will be covered by IRC mid-infrared imaging to ∼100µJy. Source confusion at optical wavelengths may also pose complications for the identification of faint infrared sources. In the optical R-band, the source density may be up to an order of magnitude higher than the far-infrared AKARI source density. Furthermore, although the advent of wide field optical multi-object spectroscopy instruments, such as AAOmega on the Anglo-Australian Telescope (Sharp et al., 2006) will make large scale follow up a reality, note that at these optical magnitudes (B<23) there will still be ∼5 optical sources per AKARI beam. Therefore, any identification /
population segregation that is possible using the infrared data alone will be of great value.

In Figure 2 the results of our analysis are presented. The top panel shows the predicted source counts over 10mJy–1Jy & 50mJy–1Jy from the models of Pearson (2007) in the AKARI FIS 90µm (left) & 140µm (right) bands respectively. The AKARI SEP survey should probe to depths of ~10mJy & 50mJy (3σ) in the 90µm & 140µm bands respectively. In the 90µm band, at brighter fluxes (S >100mJy) the source counts are predominantly dominated by cool normal galaxies due to the dust emission hump peaking in the range ~100-200µm. At fainter fluxes (S <100mJy) the warmer evolving starburst and LIRG populations dominate. The 140µm band, samples the cooler Rayleigh-Jeans regime of the dust emission hump and is dominated by cool normal galaxies and cold ULIRG sources to S ~100mJy. The fainter fluxes again see the emergence of the warmer LIRG population.

The middle panels of Figure 2 show an example colour criterion utilizing the AKARI WIDE bands. The 140µm/90µm and 90µm/140µm colours are plotted as a function of 90µm & 140µm flux respectively on the same flux scales as the source counts in the top panel in the figure. Limits in the flux and the colour corresponding to a 3σ 90µm flux limit of 10mJy and a 140µm flux limit of 50mJy are plotted as dotted lines. Immediately it can be seen that the far-infrared colours provide a reasonable discriminator of galaxy type with the more active star-forming galaxies occupying the parameter space corresponding to warmer colours (higher 90µm flux corresponding to 140µm/90µm colours ≲ 1.5 and 90µm/140µm colours ≳ 1). Note that Frayer et al. (2006) have carried out a similar exercise with sources from the Spitzer First Look Survey (FLS) although their approach was instead to fit different dust temperatures to the far-infrared colours using the MIPS 160µm and 70µm bands, interpreting a cooler dust temperature as cold infrared colours. AKARI, with its 4 FIS bands will have a greater power than Spitzer in such far-infrared population colour segregation. In addition to providing a crude separation of cool normal galaxies and warmer starburst and LIRG sources, the FIS colour segregation is also capable of identifying a distinct cold ULIRG population. These sources occupy a unique colour-flux parameter space in Figure 2. For the case of the 140µm band (right-hand middle panel), the ULIRGs occupy the parameter space defined by S(140µm)≥100mJy with 90µm/140µm colour ≲0.2. In the case of the 90µm band the ULIRGs are found at fainter fluxes of S(90µm)≤30mJy with 140µm/90µm colours ≥ 6. The models of Pearson (2007) predict that in the 90µm band, these colour selected ULIRGS will be high redshift (1<z<3) sources whilst the 140µm colour selected ULIRGs will be predominantly at redshifts z<1.5. The fainter 90µm ULIRG sample should include almost all the 140µm ULIRGs. From the middle panel in Figure 2 it can also be seen that the ULIRG samples selected in both the 90µm & 140µm bands descend and ascend respectively into the colour parameter space occu-
pied by the normal galaxies, i.e. that there is contamination of the cold ULIRG population by the cooler colours in the normal galaxy population. This contamination of ULIRGs by cool (low redshift) normal galaxies has also been reported in other colour selection studies over far-mid-infrared wavelengths (Takagi & Pearson, 2005). Using suitable additional colour criteria it is also possible to de-convolve the ULIRG sample from the cool normal galaxy population. The bottom panel of Figure 2 gives an example of the potential power of additional colour constraints to further segregate the galaxy populations. The bottom panel shows the segregation of the normal and ULIRG populations when one of the deep mid-infrared bands is used (in this case the IRC S7 7\(\mu\)m band) in conjunction with the FIS bands. The bottom left panel shows the results for the 7\(\mu\)m/90\(\mu\)m colours as a function of 90\(\mu\)m flux. The normal galaxies are separated from the cold ULIRG population by virtue of their higher mid-infrared/far-infrared flux ratio (see Figure 1). The slight remaining contamination that can be seen is actually from a hotter ULIRG population whose mid-infrared emission is dominated by an AGN. An even more significant segregation can be achieved using the 7\(\mu\)m/140\(\mu\)m colours as a function of the longer wavelength 140\(\mu\)m flux. Since the far-infrared emission of the cold ULIRGs is redshifted into the 140\(\mu\)m band, the mid-infrared/far-infrared flux ratio is even lower. In addition, the normal galaxies exhibit a smaller scatter in 7\(\mu\)m/140\(\mu\)m colours as a function of 140\(\mu\)m flux since there is less variation in the SEDs on the Rayleigh-Jeans slope than at the shorter wavelengths sampled by the 90\(\mu\)m band. The bottom panels of Figure 2 also show that, although to a lesser extent, a similar segregation can also be achieved for the AGN population.

4 Conclusions

Using a suite of SED libraries combined with a contemporary galaxy evolution model and instrument simulator, we have carried out a pilot study of, and demonstrated a method to segregate galaxy populations in large data sets in a similar manner to the methods utilized for the IRAS all-sky survey. Using simple colour criteria, the normal galaxy, starburst/LIRG & ULIRG populations can be successfully discriminated as a function of far-infrared flux without the need for large-scale optical follow up campaigns. This method has been applied to the AKARI deep survey at the SEP where it is successful in achieving a general segregation of the various extragalactic populations. The addition of more bands with a greater dispersion in wavelength can be used to further refine and decontaminate specific target populations (in this example the ULIRG and normal galaxy populations). The colour segregation criteria can thus be used to construct basic multi-component source counts without the need for expensive ground-based follow up. This is illustrated in
Figure 2. For the AKARI FIS 90µm band, the normal galaxies are identified with sources having colours over the range $1.5 \lesssim 140\mu m/90\mu m \lesssim 5$ over all values of 90µm flux. The starburst/LIRG sources are identified with sources of colours $90\mu m/140\mu m$ colours $\gtrsim 1$. The ULIRG sources can be identified by the dual colour criteria of $140\mu m/90\mu m \gtrsim 6$ & $7\mu m/90\mu m \lesssim 0.007$. In the 140µm band, the normal galaxies can be identified with sources of colour $0.2 \lesssim 90\mu m/140\mu m \lesssim 0.7$ while the starburst & LIRG sources have generally warmer $90\mu m/140\mu m$ colours $\gtrsim 0.7$. The ULIRGs in the 140µm band are defined as sources of colour $90\mu m/140\mu m \lesssim 0.2$ & $7\mu m/140\mu m \lesssim 0.02$ over a flux range $S(140\mu m) \gtrsim 100$ mJy. Although not the focus of this present work, a similar criterion can also be applied to the AGN population.

The colour-segregation method and corresponding colour segregated source counts hold great promise for the data sets that are expected from the large area surveys that are being conducted or will be conducted by the present and next generation of space-borne far-infrared telescopes such as Spitzer, AKARI & Herschel. A more detailed description of this work and application to the AKARI All-Sky Survey and possible surveys with Herschel will be presented in [Pearson & Jeong (2007)].

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Fig. 1. Selected spectral energy distributions (SED) from the spectral libraries described in the text normalized to an arbitrary flux at 60\(\mu\)m. (a) Selected normal galaxies from the libraries of Efstathiou and Dale. (b) Selected starburst galaxies from the libraries of Efstathiou and Takagi. (c) Selected LIRG sources from the libraries of Efstathiou and Takagi. (d) Selected ULIRG sources from the libraries of Efstathiou and Takagi. (e) Selected AGN from the libraries of Siebenmorgen and Efstathiou.
Fig. 2. Example of colour segregation criteria. *Top panel* shows the predicted source counts over 10mJy–1Jy & 50mJy–1Jy from the models of Pearson (2007) in the *AKARI* FIS WIDE-S 90µm (*left*) & WIDE-L 140µm (*right*) bands respectively. Results are shown for total counts and component counts (Normal, starburst, LIRG, ULIRG, AGN populations). *Middle panels* show an example colour criterion utilizing the *AKARI* WIDE bands. The 140µm/90µm and 90µm/140µm colours are plotted as a function of 90µm & 140µm flux respectively on the same flux scale as the source counts above. *Bottom panel* shows the segregation of the normal and ULIRG/AGN populations when one of the deep mid-infrared bands is used (IRC S7 7µm band) in conjunction with the FIS bands. In the figure, the *green lines* and *green open circles* represent the normal galaxies, the *blue lines* and *blue crosses* the starburst galaxies, *pink lines* and *pink plus symbols* the LIRG sources, *red lines* and *red open circles* the ULIRG sources and the *black lines* and *black filled circles* the AGN. The *diagonal black dashed lines* in the bottom 4 panels correspond to the flux limits for the SEP survey in the relevant *AKARI* band.