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Contribution of starburst mergers at $z \sim 1$ to the strong evolution of infrared and submillimeter deep surveys

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Abstract. Recent far-infrared and submillimetre waveband observations revealed a large number of Ultraluminous Infrared Galaxies (ULIGs) with infrared luminosities $>10^{12}\,L_\odot$. These sources are proposed to lie at redshifts above one, and in normally interacting systems with very dusty environments. We discussed in a previous paper that a population with a fast evolving infrared burst phase triggered by gas-rich mergers at $z \sim 1$ predicted successfully the steep slope of faint IRAS 60 μm source counts within the flux range of 100 mJy $\sim$ 1 Jy, still leaving the infrared background level at this wavelength compatible with the upper limit from recent high energy TeV γ ray detection of Mrk 501. To extend the model to mid and far infrared wavelengths, we adopt a reasonable template spectral energy distribution typical for nearby-infrared-bright starburst galaxies ($L_{\rm ir} <= 10^{12}\,L_\odot$), such as Arp 220. We construct the SED for the dusty starburst mergers at $z \sim 1$ by a simple dust extinction law and a thermal continuum assumption for the far-infrared emission. Since the radiation process at mid-infrared for these starburst merging systems is still uncertain, we assume it is similar to the MIR continuum of Arp 220, but modify it by the observed flux correlation of ULIGs from IRAS and ISOCAM deep surveys. We show in this paper that the strong evolution of the European Large Area ISO Survey (ELAIS) at 90 μm, ISO 170 μm and the Submillimeter deep survey at 850 μm could be sufficiently accounted for by such an evolutionary scenario, especially the hump of the ISOCAM 15 μm source count around 0.4 mJy. From current best fit results, we find that the dust temperature of those extremely bright starburst merging system at $z \sim 1$ would be higher than that of Arp 220 for a reconciliation of the multi-wavelength infrared deep surveys. We thus propose that the infrared burst phase of dusty starburst galaxies or AGNs from gas-rich mergers at $z \sim 1$ could contribute significantly to the strong evolution of the IRAS 60 μm, the ISO 15 μm, 90 μm, 170 μm, as well as the SCUBA 850 μm number counts, while being compatible with the current observational limits of the cosmic infrared background and the redshift distributions. The major difference of our current model prediction is that we see a fast convergence of the differential number counts at 60 μm below 50 mJy, which is about a factor of two brighter than other model predictions. Future infrared satellites like Astro-F or SIRTF would give strong constraints to the models.

Key words. galaxies: evolution – galaxies: interaction – galaxies: starburst – galaxies: Seyfert

1. Introduction

There has been much progress in the study of extragalactic evolution since far-infrared and submillimeter deep surveys detected a significant population of Ultraluminous Infrared Galaxies (ULIGs: $L_{\rm ir} > 10^{12} L_\odot$) at high redshift ($z \sim$ 1–4) (Hughes et al. 1998, 2000; Blain et al. 1999; Eales et al. 1999; Holland et al. 1999; Puget et al. 1999; Sanders 1999; Dole et al. 2000). The major interest of the present research is the nature and evolution of these sources. Due to the lack of high resolution morphological studies, the origin of these faint SCUBA sources is still not clearly understood. Local ULIGs most likely arise from major galaxy mergers with high dust extinction for the central starburst or AGN activities (Sanders & Mirabel 1996; Murphy et al. 1996; Surace et al. 1998, 2000; Scoville et al. 2000). Nevertheless, more than 50% of the high redshift ultraluminous infrared objects and the optical counterparts of ISOCAM HDF-N galaxies are suggested to show indication of galactic interactions and merger signatures (Mann et al. 1997; Smail et al. 1999; Ivison et al. 1998, 2000; Sanders 1999). Meanwhile, estimation of their spectral energy distributions suggests that these galaxies are probably the high redshift counterpart of the local ULIGs discovered by the IRAS deep survey (Barger et al. 1998, 1999; Smail et al. 1998; Trentham et al. 1999; Frayer et al. 2000). Although the exact mechanism of formation of these interesting sources is not clear, there are reasons to say that the majority of them may be major mergers of gas-rich disks accompanied by dust-shrouded nuclear starbursts or powerful Active Galactic Nuclei (AGN). SMM J14011+0252, and ERO J164502-4626.4 (HR10) are two such candidates with their central activities heavily hidden by dust extinction, and are suggested to be consistent with the evolutionary track of mergers–starbursts/AGN,

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probably elliptical galaxies in formation (Graham & Dey 1996; Cimatti et al. 1998, 1999; Frayer et al. 1998, 1999; Dey et al. 1999; Papadopoulous et al. 2001).

On the other hand, the source counts from present infrared and submilimetre surveys, such as IRAS, ISO and SCUBA all significantly exceed the non-evolving predictions. The extremely strong evolution is seen from the differential counts of the ISOCAM at 15 μm, with the remarkable upturn at $S_{15} < 3$ mJy and a fast convergence when $S_{15} \sim 0.3$ mJy. This striking feature is based on the data from several independent sky surveys (Elbaz et al. 1999; Chary & Elbaz 2001; Mazzei et al. 2001; Serjeant et al. 2001). Although there are many other possible evolutionary scenarios which could explain the present observations, the reason that we are encouraged to explore here a merger-driven galaxy evolution picture with binary aggregation dynamics is simply because the IRAS database and recent ISO and sub-mm deep surveys indicate that most of the luminous infrared sources are actually interacting/mergering systems. Also, the local IR luminosity function shows an excess over the Press-Schechter formula (Press & Schechter 1974; Lonsdale 1995; Pearson & Rowan-Robinson 1996; Guiderdoni et al. 1998; Roche et al. 1998; Rowan-Robinson et al. 1998; Dey et al. 1999; Sanders 1999; Dole et al. 2000; Efstathiou et al. 2000; Silk & Devriendt 2000; Serjeant et al. 2001; Takeuchi et al. 2001).

Considering mergers as a possible formation mechanism of Ultraluminous Infrared Galaxies both at high and low redshift, as well as their significant infrared emissions, Wang (1999) and Wang & Biermann (2000) discussed the effects of galaxy mergers on the strong evolution of the IRAS 60 μm deep survey within a binary aggregation galactic evolutionary scheme. In this model, the bright tail of the infrared luminosity function is simulated in a consistent way for both the density and luminosity evolution due to the decrease of the merger fration with cosmic time and a merger-triggered infrared burcst phase. They found that a luminosity-dependent infrared burst phase is crucial for the interpretation of the steep slope within a flux range of 10 mJy $\sim$ 1 Jy by the IRAS 60 μm deep survey. This means dusty starburst galaxies or AGNs from gas-rich mergers at high redshift may experience an infrared burst phase around a transition redshift $z \sim 1$, and fade quickly within the merger time scale of that epoch. The more massive merger systems could have such infrared emission enhanced to a higher level and decrease even faster. This kind of speculation is based on the observation that ULIGs are usually more than a factor of 20 brighter than normal starburst galaxies. Although the detailed mechanism for such enormous infrared emission is still unclear, it is believed to be related to a special stage of the merger process when the dust mass and temperature are both dramatically increased (Kleinmann & Keel 1987; Taniguchi & Ohyama 1998). Recent numerical simulations of the evolution of dusty starburst galaxies by Bekki & Shioya (2001) shows that there is a very strong photometric evolution during the merger process of two gas-rich disks, and a dramatic change of the spectral energy distribution (SED) over a cosmic time scale $T \sim 1.3$ Gyr, when the two disks of the merger become very close and suffer from violent relaxation and the star formation becomes maximal ($\sim$378 $M_\odot$ yr^{-1}). The infrared flux in this case could increase by one magnitude, especially for the far infrared wavelength range (60 μm $\sim$ 90 μm) in the emitting frame.

The redshift distribution of the contributing sources for the steep slope at faint IRAS 60 μm counts in the model of Wang & Biermann (2000) shows that the infrared burst phase around $z \sim 1$ could have comparable significance to the local IR sources. The question is then whether such an infrared burst phase, or such a population of ULIGs, could also sufficiently account for the strong evolution seen in other infrared wavelengths, especially at the ISOCAM 15 μm, ISOPHOT 90 μm, 170 μm and SCUBA 850 μm. We thus try to make a reconciliatory evolution model which could fit at least the present statistics of the multi-wavelength deep surveys.

In this paper, we will first review the binary aggregation galaxy evolution model by Wang (1999) and by Wang & Biermann (2000) in Sect. 2, where starburst/AGN activities may be triggered during the merger process, as well as an infrared burst phase from gas-rich mergers around a redshift of one. We will discuss the SED template we adopt in our calculation for the nearby starburst galaxies and a possible strong evolution of the spectral energy distribution of the dusty starburst merging systems at $z \sim 1$. We thus could further investigate whether the infrared burst phase from gas-rich mergers around redshift $z \sim 1$ is sufficient to account for the strong evolution also detected by ISO and submillimetre deep surveys. One set of cosmological parameters, namely $H_0 = 50\,\mathrm{km\,s^{-1}/Mpc}$, $\Omega = 0.3$ and $\Lambda = 0.7$ is adopted in the calculation.

2. Model

We adopt in this study the binary aggregation dynamics based on the Smoluchowski equation (1916) within a merger-driven galaxy evolutionary scheme, which simulates the evolution of a luminosity function due to galaxy mergers and predicts the redshift-dependent luminosity function of a population of galaxies evolving forwards in time from the formation epoch to match the observed local luminosity function, number counts and space distribution etc. Studies of Cavaliere & Menci (1993, 1997) show that this method could include more dynamics to describe a further step in galaxy-galaxy interactions within the scheme of direct hierarchical clustering (DHCs), and probably could help to alleviate some intrinsic problems in the DHC scenario, such as the overproduction of small objects as well as the difficulty in reconciliation between the excess of faint blue counts and the flat local luminosity function. The numerical technique to solve the Smoluchowsky equation is a Monte-Carlo approach for the inverse-cascade merger tree. Readers are referred to Cavaliere & Menci (1993, 1997), Wang (1999) and Wang & Biermann (2000) for the details of the dynamics and the techniques.

Considering different evolutionary characteristics of different morphologies, we adopt in our study a multi-component model that contains starburst galaxies, dust shrouded AGNs and spiral galaxies as three major classes of infrared emitting sources. The local luminosity functions of the spiral and starburst galaxies at 60 μm from Saunders (1990), and that of Seyferts from Ruch et al. (1993) are used to normalize the Monte-Carlo simulation. We adopt the mass-light relation of blue starburst galaxies, which is given by Cavaliere & Menci (1997) in a study of the excess of faint blue galaxies in optical surveys. The abundances of dust-shrouded AGNs are set to be 50% and 80% at local and high redshift based on the statistics from Hubble Space Telescope imaging survey of nearby AGNs and the cosmic X-ray background (Malkan et al. 1998; Gilli et al. 1999).

The modelling of a luminosity-dependent ultraluminous infrared burst phase from gas-rich mergers is described in detail by Wang & Biermann (2000). Here we give a brief review of the basic dynamics and the template SED we adopt in our model for the infrared luminous sources. We introduce also in this section the construction of a SED for the dusty starburst mergers at $z \sim 1$, normally with the luminosity $L_{\rm ir} > 10^{12}\,L_\odot$, in order to further investigate such an evolutionary scenario at mid and far-infrared wavelengths from the ISO deep survey. Considering that star formation is triggered by mergers and proportional to $M_{\rm gas}/\tau$ (τ is the dynamical interaction time scale), Cavaliere & Menci derived a mass-light ratio for dwarf galaxies, $L/L_* = (M/M_*)^\eta$ (where $\eta = 4/3$, if the cross section is purely geometrical). $L_* \propto f(z, \lambda_0, \Omega_0)$ could be used to describe a redshift dimming, or a luminosity evolution. A power law prescription of $f(z) \propto (1+z)^\beta$ is adopted in the model. Simplifying the color and K-corrections, they roughly get $L_B \propto \frac{L_*}{M_*^\eta}\,M^\eta = \frac{L_*(0)}{M_*^\eta\,f(z)\,M^\eta}$. We assume in our model a luminosity ratio $\frac{L_{60}}{L_B} \propto M^{\acute\eta}$, which is consistent with current understanding of the nature of ULIGs, where people normally believe that the extremely infrared bright phase is due to the starburst merger events with the far-infrared luminosity $L_{\rm ir}$ enhanced both by the accumulation of the dust mass and the increase of the dust temperature. This burst phase could enhance the infrared luminosity by a factor of about 20 over that of normal starburst galaxies (Kleinmann & Keel 1987; Taniguchi & Ohyama 1998; Bekki & Shioya 2001). We give $L_{60} \propto \frac{L_*(0)}{M_*^\eta}\,f(z)\,M^{\eta+\acute\eta}$. $\acute\eta = 1 \sim 1.2$ is adopted in the calculation, which not only reasonably represents an infrared enhancement of about a factor of 20 for a typical ULIG with a mass of $10^{12}\,M_\odot$ (the mass increases about one magnitude over that of normal starburst galaxies), but successfully interprets the steep slope of IRAS number counts. The scaling factor of the mass-light ratio here is normalized by the local luminosity function of the IRAS deep survey. We found from our best fit results that a population of infrared starburst sources, especially with spheroidal morphology, would have experienced very strong evolution in the past. A rate of $\beta = 3.7$ in the luminosity evolution $f(z) \propto (1+z)^\beta$ since a transition redshift $z \sim 1$ indicates a very strong evolution for such a population of starburst galaxies. This is at least comparable to, if not stronger than, QSOs (Roche et al. 1998; Lonsdale 1995; Pearson & Rowan-Robinson 1996; Rowan-Robinson et al. 1998; Sanders 1999; Franceschini et al. 1988, 2001; Dole et al. 2000). A differential dimming is simulated by $L_{\rm ir}(z - \delta z) \propto L_{\rm ir}(z)^{1-\zeta}$ below a transition redshift $z \sim 1$, in order to match the observed local luminosity function by the IRAS deep survey. The simulation gives a best value $\zeta \sim 0.4$. This power law suppression also includes another physical reality, that the infrared luminous galaxies at the bright tail of the luminosity function become gas poor faster than the less luminous ones. Besides the merger rate decrease with cosmic time, this physical effect is very important for a good fit of the steep slope at IRAS 60 μm number counts within a flux range of 100 mJy $\sim$ 1 Jy.

We reviewed above the dynamics and some important physical parameters in the current study, which are the same as those used in the previous paper of fitting IRAS 60 μm number counts (Wang 1999; Wang & Biermann 2000). In the following, we will start to construct the spectral energy distribution for dusty starburst mergers around redshift $z \sim 1$, in order to extrapolate the calculation to mid- and far-infrared wavelengths. Because of the unclear nature of the Ultraluminous Infrared Galaxies at high redshift, we do not have a good understanding of the dust environment and properties of these sources. An optically thin, single-temperature dust model is adopted as a first order approximation for a modified blackbody continuum of temperature T at far-infrared wavelength in this calculation. The formula is simply given by $S_\lambda = B_\lambda(T)\,\tau_\lambda \propto B_\lambda\,K_\lambda$. $\tau_\lambda = K_\lambda\,\rho\,{\rm d}l$ is the dust opacity, and K_λ the dust absorption coefficient ($K_\lambda \propto \lambda^{-\beta}$ of $\beta \simeq 1-2$). In this case, the flux received at wavelength λ is $S_\lambda = \frac{\Gamma\,\lambda_{\rm e}^{-\beta}\,B(\lambda_{\rm e},T)}{4\,\pi\,{\rm d}L^2\,(1+z)}$, where Γ is the scaling factor for a conservation of the dust absorbed energy and re-emitting energy, $\lambda_{\rm e} = \lambda/(1+z)$ is the wavelength in the emitting frame. A flux ratio in the observer's frame could be derived by $\frac{S_{\lambda_1}}{S_{\lambda_2}} = \frac{\lambda_{1\rm e}^{-\beta}\,B(\lambda_{1\rm e},T)}{\lambda_{2\rm e}^{-\beta}\,B(\lambda_{2\rm e},T)} \sim (\frac{\lambda_2}{\lambda_1})^{\beta+5}\,{\rm e}^{\frac{h\,C}{k}\,(\frac{1}{\lambda_2}-\frac{1}{\lambda_1})\,\frac{1+z}{T}}$, where h is Plank's constant, k is Boltzmann's constant and C is the speed of light. With a reasonable assumption for the dust emissivity power β and the dust temperature T, we can easily extend our calculation to far-infrared wavelengths. The mid-infrared emission is more complicated than that of the far-infrared which could be well described by a single temperature blackbody spectrum by cold, large grain dust. The MIR emission properties are usually dominated by the radiation field of heated small grains and PAHs. These dust grains are normally heated stochastically, and are not in thermal equilibrium with the ambient radiation field. Thus the MIR continuum is most like a power law spectrum. In this calculation, we will not provide a detailed modelling of the MIR emission feature. Instead, we only modify the template SED of the starburst galaxy Arp 220 by Silva et al. (1998), with the observational correlations of S_{15}/S_{60} by IRAS and ISOCAM deep surveys for the ultraluminous case ($L_{\rm ir} > 10^{11}\,L_\odot$) to represent the dusty starburst merging system around redshift one. The color ratio of S_{15}/S_{60} for the ULIGs is a factor of about 5 lower than the mean value of the whole sample, which may imply a very complicated process to heat small grains during the merger process (Aussel et al. 2000; Dunne et al. 2000; Saunders et al. 2000; Chary & Elbaz 2001). Although there are many indications that the MIR continuum is correlated with the temperature of large grain dust (Dale et al. 2001), there is still no exact modelling for such a process. Our goal in this paper is to construct a simple SED for those luminous starburst mergers based on various observational correlations, which not only represents the observed trend for individual samples of a certain luminosity bin ($L_{\rm ir} > 10^{12}\,L_\odot$), but matches the statistical results from the multiwavelength deep surveys. The number of sources dN in a comoving volume dV within the flux range S_λ to $S_\lambda + {\rm d}S_\lambda$, measured at wavelength λ, is defined by: ${\rm d}N = \rho(L_\lambda, z)\,{\rm d}V\,\frac{{\rm d}L_\lambda}{{\rm d}S_\lambda}\,{\rm d}S_\lambda$, $\frac{{\rm d}L_\lambda}{{\rm d}S_\lambda} = \frac{4\,\pi\,d_{\rm L}^2}{K(L_\lambda,z)}$, where $K(L_\lambda, z) = \frac{L_{\lambda_{\rm e}}\,{\rm d}\lambda_{\rm e}}{L_\lambda\,{\rm d}\lambda}$ is the K-correction, and $d_{\rm L}$ is the luminosity distance in a Λ dominated universe.

3. Results and discussions

The exact broad-band spectra of faint IR sources is still not well defined. Considering deep surveys at various IR/submm wavelengths would help to simultaneously constrain the evolution properties and the typical spectral energy distribution of such sources. We show in this section the comparison of our model prediction with the ISOCAM 15 μm survey data, IRAS 60 μm, ISOPHOT 90 μm and 170 μm (FIRBACK survey), as well as the SCUBA 850 μm data. We also calculated the redshift distribution of these sources within a certain flux range and the cosmic infrared background level. Figures 1 to 3 are the model predictions for the European Large Area ISO Survey (ELAIS). This survey covered 12 deg^2 of the sky in four main areas and was carried out with the ISOPHOT instrument onboard the Infrared Space Observatory ISO, which is at least an order of magnitude deeper than the IRAS 100 μm survey. It therefore provides an important constraint for our model of galaxy evolution. The majority of the optical identification of the detected sources are for interacting pairs or small groups of galaxies, which may indicate that the ELAIS sample includes a significant fraction of luminous infrared galaxies from galaxy mergers. Although there is some discrepancy in the data reduction, previous estimations show that the source counts are mostly in agreement with strongly evolving starburst models, with a rapid increase in the fraction of ULIGs towards high redshift (Efstathiou et al. 2000; Matsuhara et al. 2000; Serjeant et al. 2001). From our calculations, we see in Fig. 1 to Fig. 3 that the differential number counts of 90 μm, 15 μm and 170 μm for a reliable subset of the detected sources could be sufficiently accounted for by the infrared burst phase when a population of ultraluminous infrared sources with $L_{\rm ir} > 10^{12}\,L_\odot$ could be produced by the merger-triggered starburst/AGN activities at $z \sim 1$ (Kawara et al. 1998; Elbaz et al. 1999; Efstathiou et al. 2000; Dole et al. 2001). The enormous infrared emission, especially at far-infrared wavelengths is modelled by a modified black body spectrum which we discussed in the previous section. We assume that the starburst merging system has a similar MIR emission feature as Arp 220, but modified by the observed flux correlation of S_{15}/S_{60} from IRAS and ISOCAM deep surveys. We found from the calculation that the dust temperature of these starburst merging systems would be higher than that of the nearby starburst ULIGs Arp 220, with dust temperature $T = 65$ K and $\beta = 1.5$ for a best fit result. Figure 4 shows our model fitting for the differential counts of the IRAS 60 μm deep survey, and Fig. 5 shows the integrated number counts of the submillimeter SCUBA deep survey at 850 μm (Hacking et al. 1987; Moshir et al. 1992; Barger et al. 1999; Blain et al. 1999). Almost all the number counts could be reproduced quite well by such an evolutionary scenario, except for the ISOCAM 15 μm differential number counts, where our model prediction shows a slight excess at the bright part of $S_{15} \sim 2$ mJy. The reason could be that we simply adopt the mid-infrared emission feature of Arp 220 for the case of the starburst merging system around $z \sim 1$. We hope to improve the current results by further theoretical modelling and additional observational constraints for the emission properties at mid infrared bands from future infrared missions.

The infrared background in this calculation gives 2.4 nW m^{-2} sr^{-1} at 15 μm, 1.9 nW m^{-2} sr^{-1} at 60 μm, 3.8 nW m^{-2} sr^{-1} at 90 μm, 10.6 nW m^{-2} sr^{-1} at 170 μm, which are all consistent with current upper limits from TeV detections, COBE results and the resolved fraction of the CIRB by the deep ISO surveys (Funk et al. 1998; Guy et al. 2000; Hauser & Dwek 2001).

The redshift distribution of the ISOCAM 15 μm contributing sources within the detected flux range (0.1 mJy $\sim$ 10 mJy) from our model calculation is shown in Fig. 6. It gives a rough statistical finding that these luminous infrared sources cover a wide redshift range of $0.5 \sim 2.5$, peaking at $z \sim 1$. Comparing our model prediction and the redshift distribution of 15 μm sources with $S_{15} > 120$ μJy in the HDF North and the z-distribution of sources in the CFRS field (Flores et al. 1999; Cohen et al. 2000; Aussel et al. 2001), we found that the starburst mergers at $z \sim 1$ in our model are good candidates for a strongly evolving population that results in the strong evolution in mid- and far-infrared deep surveys. Recent redshift estimation from sub-mm follow-up of 10 known FIRBACK 170 μm ISO sources by Scott et al. (2000) suggests that they are in a redshift range of $0 \sim 1.5$, still consistent with our current model predictions. However, these redshift determinations strongly depend on the assumption of the dust properties. We need further accurate measurements for the robust constraints of the models.

We discussed in a previous paper that shifting the peak redshift of these ULIGs by a factor of 2 could affect the source count fitting of the IRAS 60 μm deep survey, especially for a low redshift peak ($z < 0.5$). Strong evolution of the ULIGs to $z \sim 1$ may be the most reasonable case for the existing model constraints from both the infrared deep surveys and the cosmic infrared background upper limits from high energy TeV detections, as well as the indicated star formation history by UV/optical deep surveys (Lilly et al. 1996; Connolly et al. 1997; Madau et al. 1998).

We plot the redshift distribution of ULIGs ($\nu L_\nu > 10^{12}\,L_\odot$) to understand the evolutionary properties of the ULIGs from mergers in our model. A rapid increase in the number density of ULIGs up to $z \sim 1$ is seen in Fig. 7, which is actually consistent with a scenario where galaxy merger rates increase dramatically during that epoch as seen from various observations and theoretical considerations (Zepf & Koo 1989; Carlberg 1992; Burkey et al. 1994; Carlberg et al. 1994). However, the number density of ULIGs decreases beyond $z \sim 2$–3, which may reflect a stage when merger pairs are mostly dwarfs and the infrared emissions are less than $10^{12}\,L_\odot$ even with intensive starburst activities triggered by mergers. In this scenario, an infrared luminous tail of the luminosity function may form at $z \sim 1$, with enormous infrared emission enhancement.

There is still no firm statistical basis for the classification of starbursts and AGNs from current spectroscopies. We thus adopt the observed AGN local luminosity function of Rush et al. (1993) as a model constraint, and assume in our calculations that the observed starburst galaxies and Seyferts follow the same evolutionary track, based on naive thinking that starburst/AGN may both be triggered by galaxy interactions. We know that the subtle differences in the dust emission properties could result in a different fraction of their contribution. This is still far too uncertain to discuss this here. We thus adopt only the SED of the Cloverleaf quasar which represents a phase poor in cold gas, as well as the dust enshrouded phase of F10214+4724 as two typical AGN templates in our calculation. We know from the result that the AGN contribution is only a small fraction of the whole and our current model prediction is within the present understanding of this issue, i.e. the starburst powered ULIGs are dominating over the AGN powered ones (Fig. 7) and may take over at higher redshifts and in the higher luminosity case (Lutz et al. 1998; Tran et al. 2001).

4. Summary

We have described a galaxy evolutionary scenario with galaxy mergers in a CDM cosmology, where starburst and AGN activities may be triggered by the merger events. With a reasonable assumption of the ultraluminous infrared burst phase from gas rich mergers at high redshift, we sucessfully interpreted the strong evolution of the IRAS $60\,\mu$m deep survey, leaving the infrared background still with a low limit of $1.9\,\mathrm{nW\,m^{-2}\,sr^{-1}}$, consistent with the upper limits from recent TeV γ ray detection of nearby Blazars.

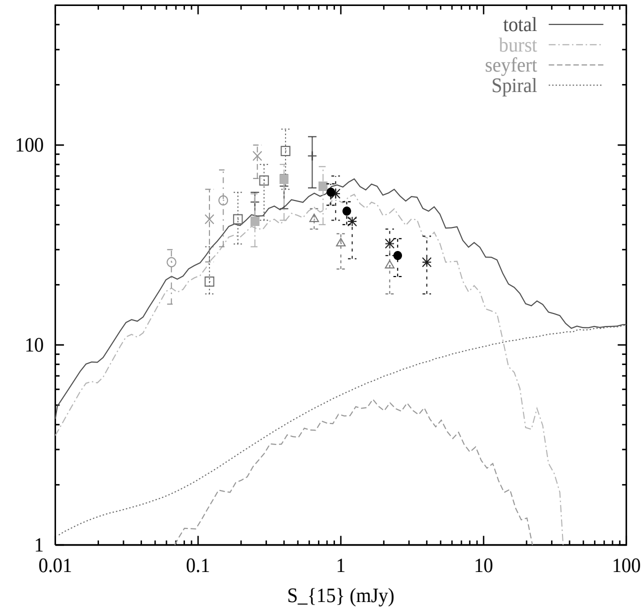

Fig. 1. The model prediction of the differential number counts of ISOCAM $15\,\mu$m normalized to the Euclidean law ($\mathrm{d}N/\mathrm{d}S * S^{2.5}$). The data points are the normalized counts from a variety of ISO deep surveys (Elbaz et al. 1999). The line represents the sum of the contribution from three populations (starburst galaxies, spiral galaxies and Seyferts). In our model, we assume that the population of starburst galaxies, especially with spheroidal morphology, are the product of galaxy mergers which would experience infrared emission enhancement because of the merger-triggered starburst activities. Their contribution to the ISOCAM $15\,\mu$m deep survey is shown by the dot-dashed line from our Monte-Carlo simulation. The dotted line corresponds to the non-evolving spiral galaxies, and the short dashed line is from Seyferts, which are assumed to have the same evolutionary track as starburst galaxies in a galaxy evolutionary scheme with galaxy mergers.

Lacking a comprehensive understanding of the gas and dust environment of faint ISO sources, especially the starburst merging system at $z \sim 1$, we adopt the template spectral energy distribution of Arp 220 by Silva et al. (1998) as typical for nearby starburst galaxies. Meanwhile, we construct a simple SED for the starburst mergers at $z \sim 1$. The far-infrared emission in such a system is modelled by a single temperature, optically thin dust law with modified black body emission. The MIR emission feature is assumed to be similar to Arp 220, but modified by the flux correlation from IRAS and ISOCAM observations. In this case, we can further investigate such a merger-driven galaxy evolutionary scenario at other infrared and submillimeter wavelengths with ISO and SCUBA deep surveys. Our calculations shows that the current results of multi-wavelength deep surveys at ISOCAM 15 μm, ELAIS 90 μm, FIRBACK 170 μm, IRAS 60 μm and SCUBA 850 μm number counts could be sufficiently accounted for by the merger-triggered infrared enhancement at $z \sim 1$ from our model with the dust temperature

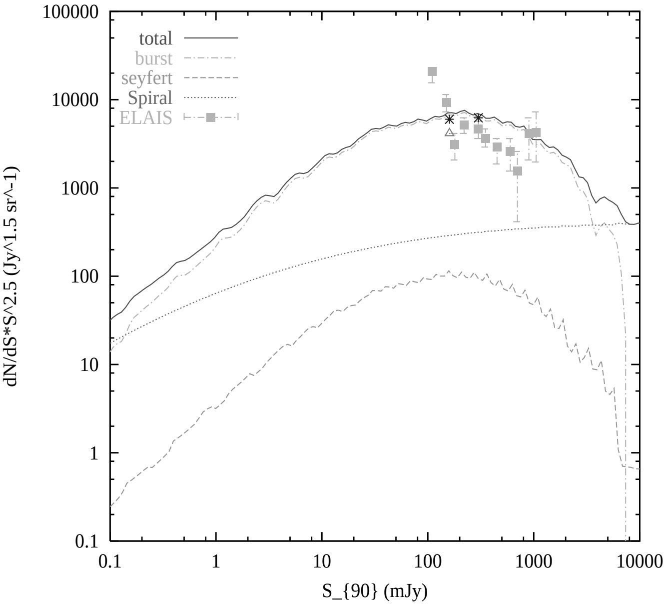

Fig. 2. The fitting of the ELAIS differential source count at 90 μm. The data are from C-90 filter of the C100 ISOPHOT detector array [filled squares: Efstathiou et al. 2000; open trianguler: Linden-Vørnle et al. (2000); star: Juvela et al. (2000)]. The meaning of the lines is the same as in Fig. 1.

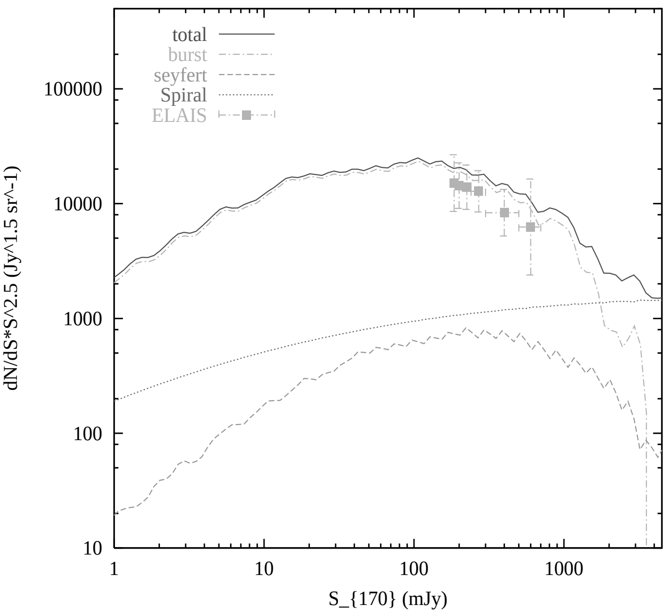

Fig. 3. The result of FIRBACK 170 μm ISO deep survey differential number count fitting from our model calculation. The data are from Dole et al. (2001).

($T \sim 65$ K, and $\beta \sim 1.5$), slightly higher than the local starburst galaxy Arp 220. Future accurate redshift measurements and multiband photometries would provide a robust model check.

The background levels at these wavelengths are estimated from our model calculation, which gives 2.4 nW m^{-2} sr^{-1} at 15 μm, 3.8 nW m^{-2} sr^{-1} at 90 μm, 10.6 nW m^{-2} sr^{-1} at 170 μm, still compatible with the cosmic infrared background level both from the upper limit

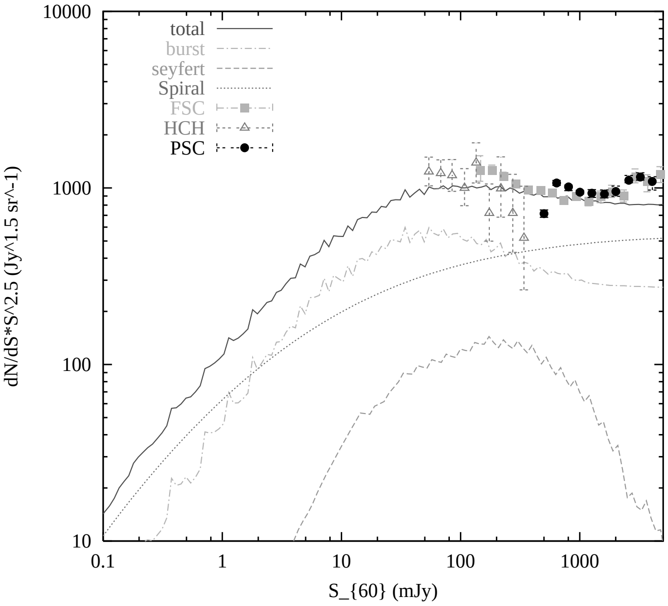

Fig. 4. The fitting of the IRAS 60 μm source counts from three major infrared emitters (starburst galxies, spiral galaxies and Seyferts). The source counts of starburst galaxies and Seyferts are from the Monte-Carlo simulation where the evolution of both activities are triggered by galaxy-galaxy interactions/mergers during structure formation. The spiral galaxy is assumed to have a mild constant star formation history, i.e. a non-evolving population in our calculation. The data are from the IRAS Point Source Catalogue (1985) (PSC), Hacking et al. IRAS deep survey (HCH), FSC from deep surveys by Moshir et al. (1992) and Saunders (1990).

of high energy TeV γ ray detection of nearby Blazars and from COBE and ISO results.

The redshift distribution of the luminous infrared sources within the ISOCAM 15 μm detection flux range (0.1 mJy $\sim$ 10 mJy) from our calculation is plotted in Fig. 6. The redshift distribution of these sources cover a wide redshift range from 0.5 $\sim$ 2.5 and peak around a mean redshift of $z \sim 1$.

We also plot the redshift distribution of ULIGs ($\nu L_\nu > 10^{12} L_\odot$) in Fig. 7. It shows a strong increase in the ultraluminous infrared population until a mean redshift $z \sim 1$, and decreases by a factor of about 2 by $z \sim$ 2–3. This is probably the major difference between our current calculation and other models, and indicates that the infrared luminous tail may be produced at the cosmic epoch of $z \sim 1$, when the merger rate and the size of parent galaxies are suitable for such an infrared emission enhancement.

A brief discussion about the fraction of contribution from AGNs and starbursts from our calculation is given in Sect. 3. We assumed in the model a similar evolutionary track for the starburst galaxies and AGNs based on the idea that both AGNs and starbursts may be triggered by galaxy interactions, where the AGN population is constrained by the observed Local Luminosity Function of Seyferts from Rush et al. (1993). Given the uncertainty of the dust properties of ULIGs, especially for those harboring an AGN in the center, we adopt here only

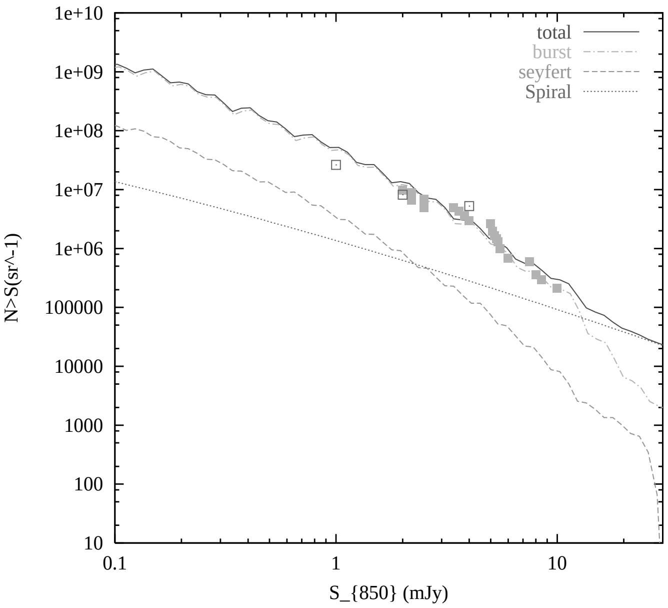

Fig. 5. Integral number counts at 850 μm. The open squares are from Blain et al. (1999), and the filled squares are from Barger et al. (1999). The meaning of lines are the same as in previous figures.

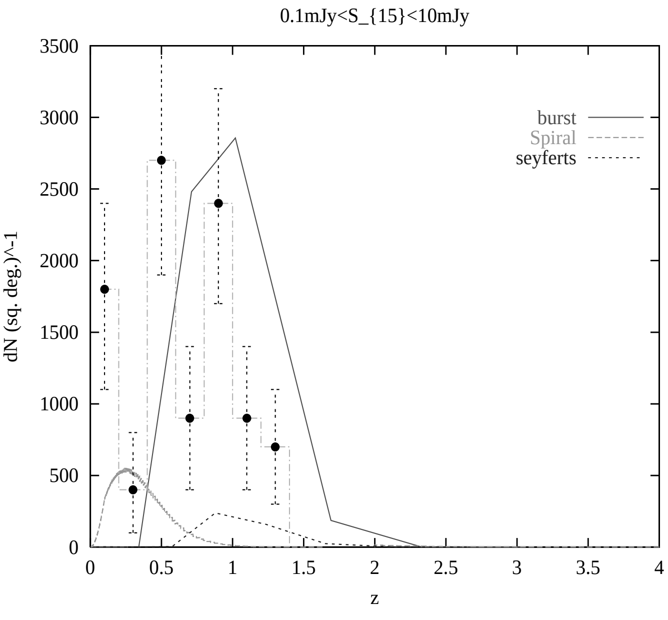

Fig. 6. The redshift distribution of three infrared contributors (starburst galaxies, spiral galaxies and AGNs) at a flux range of 0.1 mJy $\sim$ 10 mJy at 15 μm from our model calculation. The redshift of these ISO far-infrared sources would cover a wide range and peak near $z \sim 1$. We include also the AGN contribution in our model based on the observed AGN Local Luminosity Function from Rush et al. (1993).

two typical SED templates of the Cloverleaf QSO and F10214+4724. In this case, we give a rough estimation of the relative abundance of AGN and starburst-powered ULIGs ($L_{\rm ir} > 10^{12}\,L_\odot$) of ~1/5, which seems to be close to the recent submillimeter observations of Chandra X-ray sources (Almaini et al. 1999; Barger et al. 2001; Gunn & Shanks 2001).

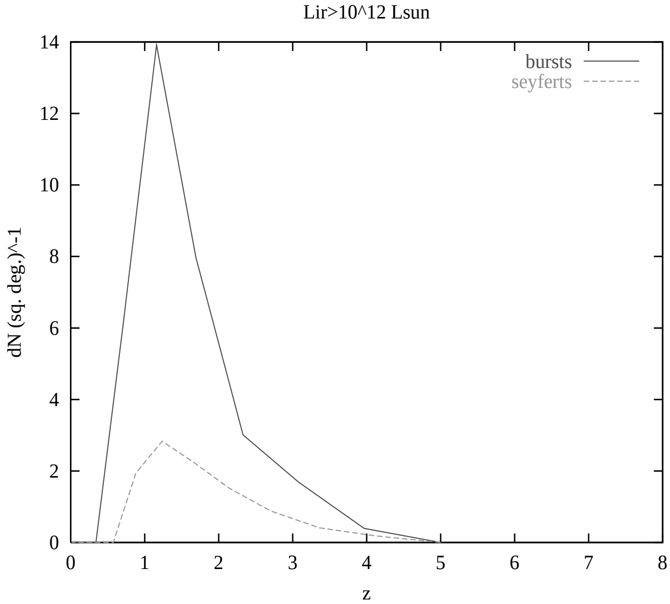

Fig. 7. The redshift distribution of ultraluminous infrared sources (starbursts or AGNs) with $L_{\rm ir} > 10^{12}\,L_\odot$ from our model calculation. The number density of the ultraluminous infrared sources increases dramatically until $z \sim 1$, but quickly decreases afterward.

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