When and How did Galactic Spheroids Form?

Dr Frank Masci, Internal Working Paper, Draft 2: 5/4/2000

1 Introduction

How elliptical galaxies and the bulges of spirals formed is one of the key questions of modern cosmology. Galactic bulges are centrally concentrated, high surface brightness systems which have undergone more collapse than galactic disks. Their high density indicates either significant gaseous dissipation occured during their formation or, they formed at very high redshift $z > 10$ (Peebles 1989). Studies of stellar populations in the bulges of field galaxies at intermediate redshifts $0.4 < z < 1$ are consistent with them being 'old', forming ≈ 10 Gyr ago (Abraham et al. 1999). Recent advances in the understanding of star formation and feedback mechanisms through simulations of hierarchical clustering predict spheroids to form their stars at $z \simeq$ 1-2 (Baugh et al 1998; Carlberg 1999), and that a majority should be obscured by dust at optical/near-Infrared wavelengths (Franceschini et al. 1998; Kauffmann & Charlot 1998). Such epochs are only now starting to be explored with far-IR/sub-mm instrumentation. Our proposed survey in particular will play a key role at probing redshifts $z \lesssim 1$, or at least the tail of the spheroid formation epoch.

A number of theories exist for the formation of galactic spheroids and ellipticals: primordial 'monolithic' collapse of individual gas clumps (Eggen et al. 1962; Arimoto & Yoshii 1987) and variations thereof (Peacock et al. 1998; Jiminez et al. 1998), hierarchical merging of pre-formed galaxies (Toomre & Toomre 1972; Kauffmann et al. 1994; Baugh et al. 1996), infall of gas-rich satellites onto pre-existing dark matter disk halos (Cole et al. 1994; Carlberg 1999), and 'secular' evolution where bulges form relatively late by gas-inflow from their pre-existing gas-rich outer disk (Norman et al. 1996).

Of the above models, 'monolithic' and 'merger' scenarios are the main competitors. Although no conclusion is yet firmly established, merger models have become increasingly popular since the deep optical/near-IR surveys from HST. Widespread observational evidence for a paucity of evolved (red) spheroids at $z \gtrsim 1$ in optical/near-IR surveys has placed monolithic 'rapid formation' at $z_F \sim 2 - 5$ in somewhat of a dilemma (eg. Zepf 1997; Barger et al. 1999; Menanteau et al. 1999). Some authors however (eg. McCracken et al. 2000) claim that possible uncertainties in morphological identification and field-to-field variations in these studies could still make such models a serious contender. On the other hand, the observed properties of ellipticals and bulges: dynamical disturbances such as shells/ripples, transient dust lanes, multiple and counterrotating cores, globular cluster distributions (Kormendy & Djorgovski 1989; Schweizer & Seitzer 1992) all support a merger (or sattellite accretion) hypothesis for spheroid formation. Furthermore, the formation of structure through hierarchical clustering is a picture predicted by the standard cold dark matter (CDM) cosmology.

While there has been much effort on predicting the counts and colors of evolved spheroids at high redshift in the optical/near-IR, there has been little motivation on extending these predictions to their formation phases when they were expected to be obscured in dusty starbursts emitting strongly in the mid-to-far infrared. The main difficulty has been bridging the gap (or identifying the transition) between 'dusty starburst' phase and specific 'galaxy type' - known or otherwise. As a working hypothesis, we therefore assume that the *majority* of starbursts identified at mid-to-far infrared wavelengths in the intermediate-to-high redshift range: $z \sim 0.5 - 1$ are merger/accretion induced 'events' that form the spheroids we see today, including the bulges of spirals.

At least one observational distinction can be made between the monolithic and merger/accretion scenario using infrared observations: In the 'classical' monolithic model where the bulk of stars form at $z \sim 2-5$, the associated dusty starbursts should also predominately reside at these redshifts. Their space density will be conserved and they may undergo substantial IR-luminosity evolution before the dust is expelled. Under this scenario, relatively few (or essentially no) dusty spheroid-progenitors are expected at $z \lesssim 1$. In a scenario involving continuous mergers, starbursts should be prevalent at $z \lesssim 1$, with evolution in number density primarily controlled by the merger rate. This indeed appears consistent with the deep ISO surveys at 15μm (Elbaz 1999), which find a large population with $L_{IR} \gtrsim 10^{11} L_{\odot}$ undergoing strong evolution within $0 \lesssim z \lesssim 1$. Due to their relatively large number, it is hard not to associate these sources with the formation of some component of the local spheroid population. The merger/accretion scenario therefore presents us with testable predictions in the mid/far-IR to $z \simeq 1$, ideally suited for comparison with a large area survey of the intermediate-to-low redshift universe.

We present here predictions of number counts expected in the MIPS bandpasses using a scenario where spheroids form from the continuous accretion of gas-rich satellites. Color diagnostics using the IRAC bandpasses and other wavelengths are also presented. Within a CDM framework, a simple model involving wind-regulated accretion of gas-rich satellites has recently been proposed by Carlberg (1999). The model has attained considerable success at explaining some general bulge properties: the 'Kormendy (density-size) relations', residual angular momentum distributions, and mass-metallicity correlations. We are currently collaborating with R. Carlberg on making predictions of associated 'starburst' number counts in the mid/far-IR, and results will appear in Masci, Carlberg & Lonsdale (2000). Section 4 contains a brief outline of the model and results.

2 Previous Work and Limitations

The recent strong evidence from SCUBA and ISO deep surveys for the existence of morphologically disturbed/peculiar galaxies at high redshifts with star-formation rates (SFRs) $> 100 M_{\odot} yr^{-1}$ (Blain et al. 1999; Elbaz 1999) is consistent with proto-spheroids forming via merger induced starbursts. Although much less dramatic in statistical terms, this process is thought to be ongoing today through the 'ULIRG' phenomenon. These results have been explained in the framework of 'Semi-analytic' CDM models of hierarchical galaxy formation (eg. Guiderdoni et al. 1998). Given their success at accounting for observations in the optical/near-infrared wavebands, they suffer serious limitations when extended to the far-IR/sub-mm regime. Unphysical and unmotivated assumptions often need to be invoked to acheive a good match with the data. In order to account for the sub-mm SCUBA data, Guiderdoni et al. (1998) need to arbitrarily incorporate an additional population of ultraluminous galaxies (with $L_{IR} > 10^{12} L_{\odot}$) into their models. Such models also involve a large number of free parameters and the interplay between them makes it difficult to identify what process is driving a particular observation.

In general, recent estimates of 'unobscured' SFRs through far-IR and sub-mm studies has lead to an unanticipated dilemma in the CDM modelling community: both the high abundance of high SFR systems ($> 100 M_{\odot} yr^{-1}$), and their high redshifts ($z \sim$ 2-3) are inconsistent with simple first order CDM predictions. The simplest models predict late star-formation with rates no greater than a few-tens $M_{\odot} yr^{-1}$, and hence with very little dust at $z > 1$ (White & Frenk 1991; Somerville et al. 1999). Both Blain et al. (1999) and predictions from our bulge-building model (Masci, Carlberg & Lonsdale 2000; see details below) elucidate on this issue and two basic requirements to account for all the avalaible deep IR/sub-mm data are: *strong evolution* in both the efficiency of luminosity generation (either powered by star formation or AGN) *and*, the merger (or accretion) event rate.

3 Motivation

In conjunction with our simulations for spheroid formation, a moderate to moderately deep survey in the MIPS wavebands will enable us to address the following:

1. What physical parameter(s) drive spheroid evolution? Efficiency of gas consumption by star formation (and/or an AGN) *or* merger rate?

2. What fraction of integrated far-IR source counts and hence the cosmic infrared background (CIRB) can be attributed to the process of bulge-building?

3. Is bulge building an energetically important process (as a fraction of the bolometric energy density) in the early universe?

4. What is its contribution to the star formation history of the universe, and, how does it compare with the accretion history from AGN fuelling?

5. Since our models predict the majority of spheroids to form at $z \lesssim 1.3$ (see below), how is the associated starburst activity related to the higher redshift, luminous SCUBA population? If indeed the SCUBA sources are forming one component or population of local spheroids (including massive ellipticals), can we bridge the gap between different epochs of bulge formation? Do the bulges of less luminous bulges (eg. spiral

bulges) form later? Large number statistics of the moderate redshift universe ($0.5 < z < 1.3$) that spans a wide luminosity range will shed light on this issue.

4 A Simple Empirical Model for Spheroid formation

Given the complexities and unphysical assumptions in previous models for explaining existing far-IR/sub-mm data, we have developed (in collaboration with R. Carlberg) a simple model for the assemblage of galactic bulges. Full details of the basic framework are presented by Carlberg (1999) and methods for predicting IR-counts and comparison to observations can be found in Masci, Carlberg & Lonsdale (2000).

The model contains very few parameters of which a majority are fixed empirically. It involves a scenario whereby gas-rich satellites are accreted onto pre-existing 'fiducial' dark matter disk-halos and the initiation of starbursts develop winds to make the accretion self-regulating. The model uses a Monte Carlo simulation and essentially takes as input the following: a merger (or satellite accretion) rate (fixed empirically from studies of galaxy clustering), a mass spectrum for the pre-accreted satellites provided by the standard CDM paradigm, and stellar feedback (or wind) parameters for determination of gas stripping fractions.

Assumptions for the derivation of far-IR source counts - essentially the associated starburst events integrated over time for all forming bulges are as follows:

1. The final, fully assembled bulges produced by the simulation are normalised to the total space density of local bulges from optical/near-infrared surveys (eg. bulges of spirals, ellipticals etc..). This fixes the representative comoving volume of the simulation. This is the *first time* such a constraint is imposed in predicting the formation history of observed present day bulges through dust obscured starbursts in the far-IR.

2. The star formation rate is given by $SFR = M_{acc}/\Delta t$ with starburst timescale $\Delta t \simeq 10^7 yr$. Furthermore, all accreted gas goes into feeding a starburst with given efficiency and no AGN fuelling is involved.

3. The above SFR is modified by a redshift dependent efficiency parameter

$$\epsilon(z) = 1 - [1 - \epsilon(0)] \exp(-\beta z), \quad (1)$$

   where $\epsilon(0)$ (the local SF efficiency) and β are model dependent parameters (see below). Such a dependence is motivated from modelling of the deep ISO-15μm (Roche & Eales 1999) and SCUBA-850μm (Blain et al. 1999) data.

4. The far-IR luminosity is linked to the above SFR through an empirical relation derived from local observations (eg. Smith et al. 1998). This

relation depends on the mass limits of the stellar IMF and star-formation timescale. A Miller & Scalo (1979) IMF is assumed with mass range: $1M_{\odot} < M < 100M_{\odot}$.

5. An IR-SED library for starbursts from the spectrophotometric models of Devriendt (1999) is assumed for the K-corrections. A dependence of SED shape on IR-luminosity that reflects the observational correlations of IRAS flux ratios with L_{IR} is taken into account.

In the context of conventional models for hierearchical clustering, we must emphasise that our model represents a somewhat different and simplified scenario, although the main physical parameters are equivalent. Our main assumption is that *only* gas in the accreted satellite (the secondary) is converted into stars with some given efficiency (3 above). Pre-existing gas in the primary object from previous accretions does not contribute to the starburst. For comparison, local mergers are known to occur between two or more gas rich systems where presumably all the gas is involved in the starburst. Whatever the arrangement and origin of the pre-merger gas however, the main constraint is that we re-produce the 'optically observed' local bulge population. The number density of starbursts observed at any epoch is essentially proportional to the merger rate in any merger model and is independent of where and how much gas is converted into stars. The bottom line is that the *mass* of gas converted into stars must always be the same to achieve our final desired bulge mass. Incorporating additional gas in the merger (eg. the primary) will simply require us to downscale the star-formation efficiency by a factor of a few and will only become important towards low redshifts. At high redshifts, essentially all gas will reside in the secondary satellite that falls onto a pre-existing dark-matter halo. Furthermore, the empirical high-z merger rate in our model is large enough that $\gtrsim$70% of bulges are fully assembled by $z \simeq 0.5$ (Carlberg 1999). Therefore, residual gas towards low redshift is left to accumulate and its fate is not modelled here. It may be blown out when the central starburst is terminated, perhaps contributing to a disk and eventually forming stars quiescently, or it may heat up and contribute to the hot X-ray emitting gas as seen in local ellipticals. We defer these issues to a future study.

While the space-density normalisation and starburst SEDs (assumptions 1 and 5 above) are strongly constrained by observations, assumptions concerning star formation timescale and its IMF (2 and 4) are not. Nonetheless, our model is found to be relatively insensitive to these parameters and we have fixed them to the values quoted above. Assumption (3) however, concerning the efficiency at which gas is converted into stars as a function of z, has a significant affect on faint counts relative to those at bright fluxes.

Figure 1 compares our model predictions to ISO (15μm) and IRAS (12, 60μm) observations. The deep ISO (15μm) surveys constitute the best available statistics for probing evolution within the range $0 < z \lesssim 1.3$ (Aussel et al. 1999). We have assumed two models defined by two different forms for evolution of the star-formation efficiency (Eqn.1). The models are defined by $(\epsilon(0), \beta) =$(0.1,1) and (0.05,2), which correspond to an increase in star formation efficiency by factors of ≈ 6.7 and ≈ 17 respectively

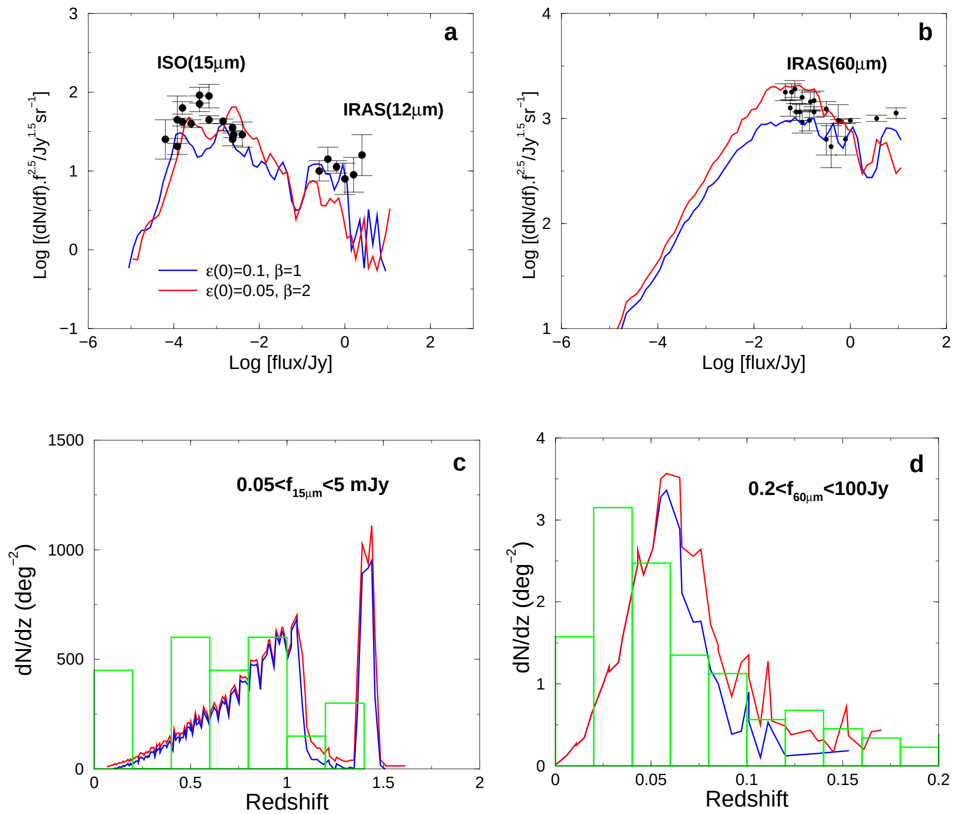

Figure 1: **(a)** Euclidean normalised 15μm differental counts. 15μm data is from a number of deep ISO surveys compiled by Elbaz (1999). 12μm data is from Spinoglio et al. (1995). **(b)** Same as (a) for 60μm. Data is from a number of IRAS surveys taken from Hacking & Houck (1987), Rowan-Robinson et al. (1990) and Saunders et al. (1990). **(c)** Redshift distribution at 15μm with data (green histogram) from deep ISO fields by Aussel et al. (1999). **(d)** Redshift distribution at 60μm with data provided by C. Lonsdale (private communication). Models are shown for two assumptions of evolution of the star formation efficiency as parameterised by Eqn.(1).

from $z = 0$ to $z = 1$. The models assume an open cosmology with $\Omega = 0.3$, $\Lambda = 0$ and $H_0 = 65 \mathrm{km\,s^{-1} Mpc^{-1}}$ in accord with existing observations.

We must emphasize that our models in Figure 1 *only* predict bulge-building starburst events. Although merger-induced 'violent' starbursts could dominate the mid-to-far-IR counts, other populations such as AGN and quiescently evolving (constantly star forming) disks will also contribute. As inferred from models that re-produce the X-ray background, simple estimates for the AGN fraction at 15μm and 60μm are 10-20% (independent of redshift and luminosity to first order; Masci et al. 2000). Quiescent star-forming disks are estimated to comprise $\approx$ 20% in the faint 60μm IRAS surveys (Pearson & Rowan-robinson 1996) and are expected to contribute less at 15μm due to their 'cool' emission. Furthermore, quiescently evolving (or essentially non-evolving) disks will not contribute significantly at the faintest fluxes $\sim$ 0.1-1 mJy. The fraction of local systems undergoing interactions (and mergers) in (bright) local IRAS counts also provides a strong constraint on our models at bright fluxes. For our relevant luminosity range $10 \lesssim \log{(L_{IR}/L_{\odot})} \lesssim 11.5$, Surace et al. (2000) find a merger fraction of $\approx$ 70% at $f_{60\mu m} > 5$ Jy, consistent with the remainder being AGN (Seyferts) and cool disks as discussed above.

The models in Figure 1 are broadly consistent with the available ISO and IRAS data and the main conclusion is that evolution in both merger rate and star formation efficiency is required to acheive acceptable fits. This conclusion was also reached by indepedent modelling of these counts by Roche & Eales (1998) and Blain et al. (1999). In conjunction with fits to the ISO/IRAS data, further quantities inferred from our model are contributions of $\approx$50% and $\approx$70% to the CIRB at 15μm and 60μm respectively from bulge-building starbursts. Furthermore, a fraction of $\approx$10% and $\approx$50% of the global star-formation rate density at $z = 0$ and $z = 1.5$ respectively can be attributed to bulge-building alone.

5 The Need for SIRTF

A limitation of our model is its inability to re-produce the deep 850μm (SCUBA) source counts at $2 < z < 4$. As discussed above, this is a limitation imposed by galaxy evolution models in a CDM framework. The CDM power spectrum which succesfully explains and relates hierarchical clustering to primordial density fluctuations is inadequate to account for gas mass concentrations $> 10^{11} M_{\odot}$ on galaxy scales required to feed starbursts at $z > 2$. Although the model may pose a problem for predicting star-formation rates at these epochs, the 15μm ISO counts which typically reside at $z \lesssim 1$ are broadly consistent with our model predictions. As discussed above, bulge-building through mergers and accretions appears to be an ongoing process from $z \sim 1$ to the present, and this represents a lookback time of $\simeq$ 10 Gyr - a significant fraction of the age of the universe where much evolution is expected. Thus, regardless of the inability of CDM theories to fully explain galaxy evolution at $z > 2$, they can still be used to constrain cosmologically important processes such as SF history, and its relation to merger rate evolution within $0 < z < 1$.

Given that evolution in both merger rate and star formation efficiency are required to explain the deep ISO/IRAS data, the main question we wish to address is: Which of these two processes dominates during bulge-building? The merger rate in our model is fixed from studies of evolution in galaxy clustering to $z \sim 1$ (Carlberg 1999). Given this is an adequate assumption (to first order), evolution in star-formation efficiency therefore remains our free parameter describing the evolutionary aspect of bulge-building. Guided by fits to the deep ISO/IRAS data above, number counts in the MIPS wavebands (Figure 2(a)) could in principle constrain these quantities. Figures 2(b) and 2(c) respectively show the redshift ranges and range of SFRs (with corresponding luminosities) we will be sensitive to. These assume our 'minimal' model with $\epsilon(0) = 0.1, \beta = 1$ (see section 4).

Well defined, complete samples of starbursts selected using a wide range of IR wavelengths will be required to better constrain these models. Given the limited information regarding the nature of the faint 15μm ISO sources (eg. Elbaz 1999), one cannot be certain whether they do indeed sample a population of 'bulge-building' starbursts. There has been some speculation that samples selected at 'short' mid-IR wavelengths (eg. Spinoglio et al. 1995) will contain a high proportion of AGN by virtue of their warm color excess. This becomes increasingly important at high redshifts where shorter rest wavelengths are sampled. Furthermore, 'warm' starbursts where dust obscuration (and hence dust content) of star-forming regions is relatively low, may also be preferentially selected. Their properties may not genuinely reflect classical starbursts selected from previous far-IR surveys. A more accurate characterisation of 'starburst nature' over many wavebands is therefore necessary. A large (and deep) far-IR survey that extends the work of IRAS is therefore needed to address these uncertainties.

A large area, moderate-depth survey in the MIPS 24, 70 and 160μm wavebands will enable us to detect at least 6×10^4, 3×10^5 or 3×10^3 starbursts within 90 square degrees in each band respectively. Our nominal 70μm sensitivity will allow us to probe a maximum redshift $z \simeq 1.25$ (Figure 2(b)). 50% of 70μm detections are expected to reside at $z \gtrsim 0.6$. These statistics will allow us to

1. Trace bulge formation from $z \sim 1$ to the present over a large luminosity range and quantify its contribution to the CIRB and global star-formation history using detailed model fits across all MIPS bands.

2. Determine the relative importance of evolution in merger rate and star formation efficiency, and explore their dependence on luminosity and galaxy environment.

3. Compile broadband SEDs from the MIPs bands for a large sample of starbursts to better ascertain their dust properties and explore any possible dependence on luminosity, galaxy environment.

6 Further Work with Complementary data

Given a large sample of far-IR selected galaxies, we plan (collabs?) to carry out a comprehensive multiband follow-up (in the optical and near-IR) to further constrain

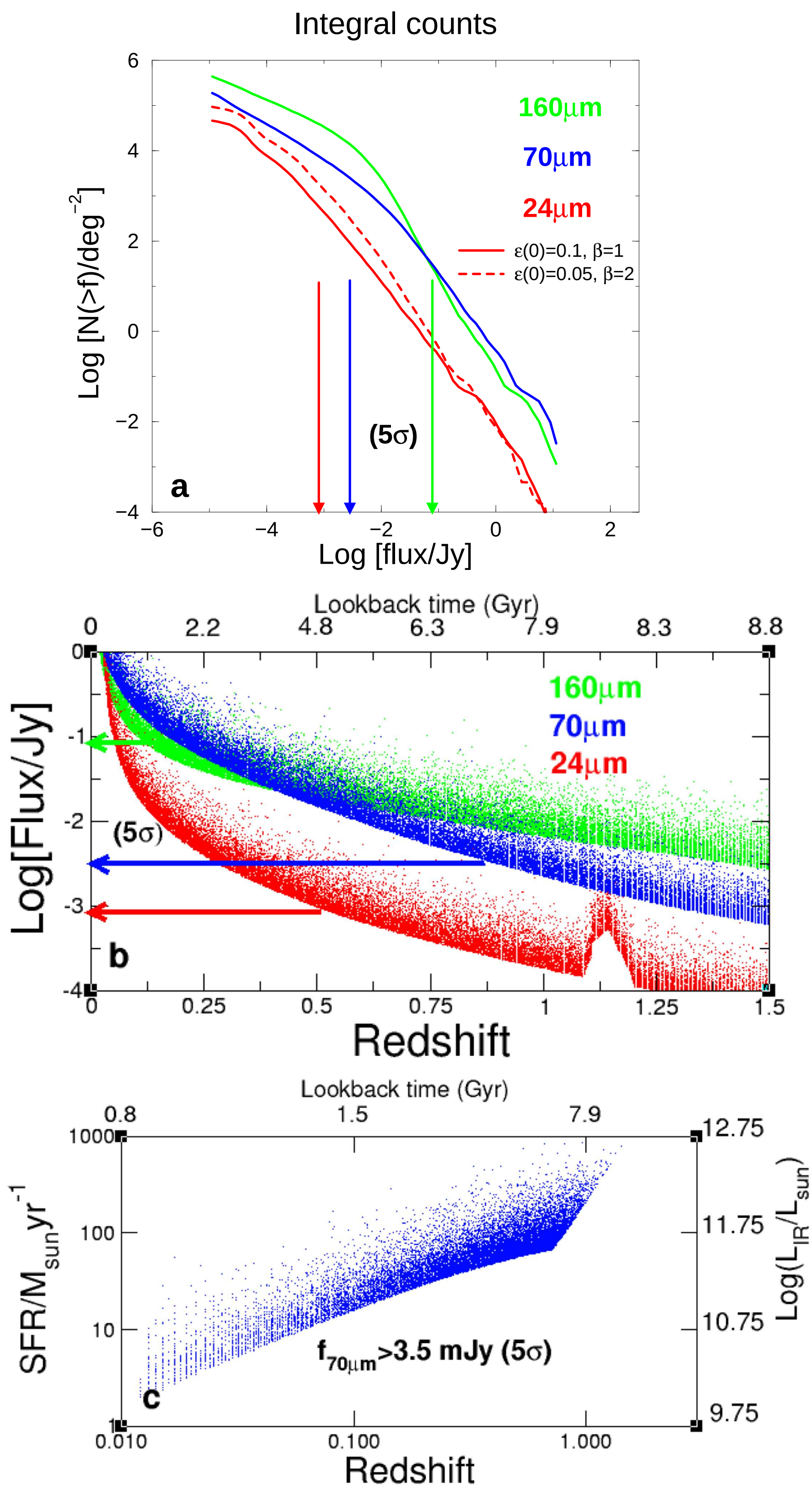

Figure 2: **(a)** Integral counts in the MIPS bands. Dashed red curve at 24μm corresponds to our 'maximal' model and all other curves correspond to our 'minimal' model. Vertical arrows are 5σ sensitivities. The 160μm limit is attributed soley to confusion noise. **(b)** Flux-redshift scatter plot for all bulge-building events with 5σ sensitivities shown. Down to our nominal sensitivities, the 70μm band appears to probe the highest redshifts. **(c)** Range of star-formation rates (and infrared luminosity) of bulge-building starbursts expected in a 70μm survey down to nominal sensitivity of 3.5 mJy.

the properties of bulge-forming starbursts. In particular, we plan to

1. Determine photometric redshifts by combining IRAC and MIPS data (see section??). Given the good reliability and large statistics from these redshift estimates, we can determine for the first time a bolometric luminosity function for starbursts. One could then compare its evolution to that of accretion powered sources (ie. AGN) - see section? for our Chandra collaboration. Given the strong evidence for a connection between spheroid mass and the mass of centralised massive dark objects in the local universe (eg. Magorrian et al. 1998), a relevant question is how spheroid formation relates to the growth and evolution of central black holes.

2. Use deep radio imaging with the VLA (collaborator: F. Owen) to better characterise starbursts through their far-IR-radio correlation. Does this relation evolve or depend on other physical properties such as starburst age or luminosity? Figure 3 shows the predictions from our bulge-building model. The observed radio counts are seen to rapidly converge with bulge-building starbursts at $\lesssim 150\,\mu$Jy.

3. Determine the relationship between samples of faint galaxies selected in the optical/UV (eg. the Lyman break galaxies) and far-IR galaxies. Could there be an evolutionary connection? Are these galaxies part of the same underlying intrinsic population with varying degrees of dust enshroudment?

7 Exploring the Passive Phases with IRAC

The above discussion primarily focussed on the expected counts and evolution of starbursts associated with the 'active' and re-occurring dusty phases of spheroid formation. Eventually however, a bulge will emerge between the obscured starburst phases given that the optically-thick dust is blown away on timescales comparable to that of the starburst. The systems will then evolve passively, or nearly so until a later starburst initiates another dusty phase. Although the mechanism of dust-ejection/destruction is not well understood, we assume it applies in the simple model presented here. The timescale for the obscured starburst phase ($\approx 10^7$yr) is typically much shorter than the average timescale between succesive re-occuring bursts ($\approx 10^9$yr) that we can expect to sample a large fraction of forming bulges at optical/near-IR wavelengths in their dust-free or more plausibly, optically-thin phase. Conservatively speaking, even if the *dusty* phase lasted for $\approx 10^8$yr, we have a 90% chance of seeing a bulge in its un-obscured phase. Observations of the passive evolutionary stages at these wavelengths can therefore provide an independent test of the bulge-building model.

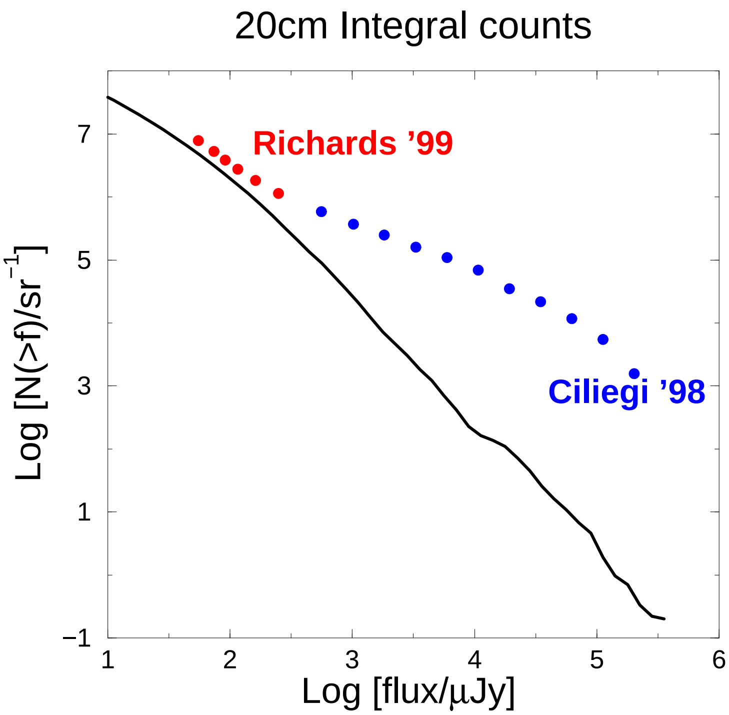

Figure 3: Integral counts at 20 cm (1.4 GHz). The model assumes our 'maximal' star-formation efficiency parameters: $\epsilon(0) = 0.05, \beta = 2$ (see text).

We have predicted the distribution of observed optical-to-near-IR colors from our model by following self-consistently the starburst history of each bulge in the simulation. Depending on the time at which a forming bulge is observed, we have modelled the SED as two separate components: if our observation epoch falls within a time of 10^7yr pro-ceeding a starburst event, we assumed an empirical, local starburst SED (depending on luminosity). If however we are outside this time interval, we modelled the SED at that epoch as the superposition of age-dependent synthetic stellar spectra (with no extinction) from all preceeding starburst events, weighted by the respective star-formation rates. These make use of the GISSEL96 (Bruzual & Charlot 1995) spectral synthesis code and assume 'instantaneous' bursts of solar metallicity. Roughly speaking, a factor of two dispersion in metallicity results in a dispersion ≈ 0.8 mag in optical-near-IR color, independent of the population age.

Figure 4(a) shows the observed IRAC(3.6μ)m-optical colors as a function of redshift for a random set of 10 bulge histories from the simulation. Figure 4(b) shows an observed color-color plot involving the IRAC(3.6μ)m, $B(0.4\mu$m) and $I(0.8\mu$m) bands for three redshift ranges. We must emphasise that the density of points does not reflect the relative number of sources between the different redshift ranges. The important feature from this plot is the fraction of red spheroids (with $\log(3.6/0.4) \gtrsim 3.5$) relative to blue ones as a function of redshift. We must note that these blue spheroids are essentially those young systems which have just emerged from a starburst phase and could indeed have redder colors if dust from this phase has not fully cleared. The reddening vector in this plot gives some indication of the magnitude expected. The prediction in Fig.4(b) should be compared to those of 'extreme' monolithic models where essentially all spheroids at $z < 1$ should have red colors due to evolved stellar populations formed at $z \sim 3 - 5$.

The ratio $\log(3.6/0.4) \gtrsim 3.5$ is equivalent to a color $R - K \gtrsim 6$ mag for sources at $z \gtrsim 1$. Such objects will appear as *extremely red objects* (EROs) and their interpretation as evolved spheroids will shed light on the epoch of massive spheroid formation. For our proposed sensitivity: $S_{3.6\mu\mathrm{m}} = 9.4\mu$Jy ($5\sigma$), our model predicts a surface density $\approx 150\,\mathrm{deg}^{-2}$ for objects with $R - K > 6$ at $z > 1$. This is consistent with recent findings from deep K-band surveys (eg. Thompson et al. 1999) and suggests that a majority could indeed represent evolved spheroids.

A survey in the IRAC 3.6μm bandpass (to 9.4μJy-5σ) will detect passively evolving spheroids of $\approx 0.2 - 0.7L_*$ (ie. not fully assembeled into luminous L_* systems) out to redshifts $z \simeq 1.8 - 2.5$. An obervational test of our model through color-color diagnostics will first require a dedicated effort of isolating spheroid-like morphologies using automated classification procedures, similar to those applied in the Hubble Deep Fields (eg. Abraham et al. 1996). Selection in the IRAC bandpasses will be well suited for this procedure due to first, IRAC's good resolution (really????), and second, from the fact that such wavelengths are likely to sample relatively evolved systems entering their passive phases with little bias from dust reddening. Sources exhibiting a strong dust excess in the near-IR will pose a problem however, and will require follow-up in the optical for further inference.

To summarise, a moderate depth survey with MIPS will provide us with a large number of 'conjectured' bulge-building starbursts, or spheroids in their obscured phases out to $z \simeq 1$. Combined with optical follow-up and further morphological classification work, IRAC will enable us to select a large sample of spheroids in their passive phases out to at least $z \simeq 1$. Both number counts and color diagnostics will allow us to strongly constrain merger models and their competing scenarios.

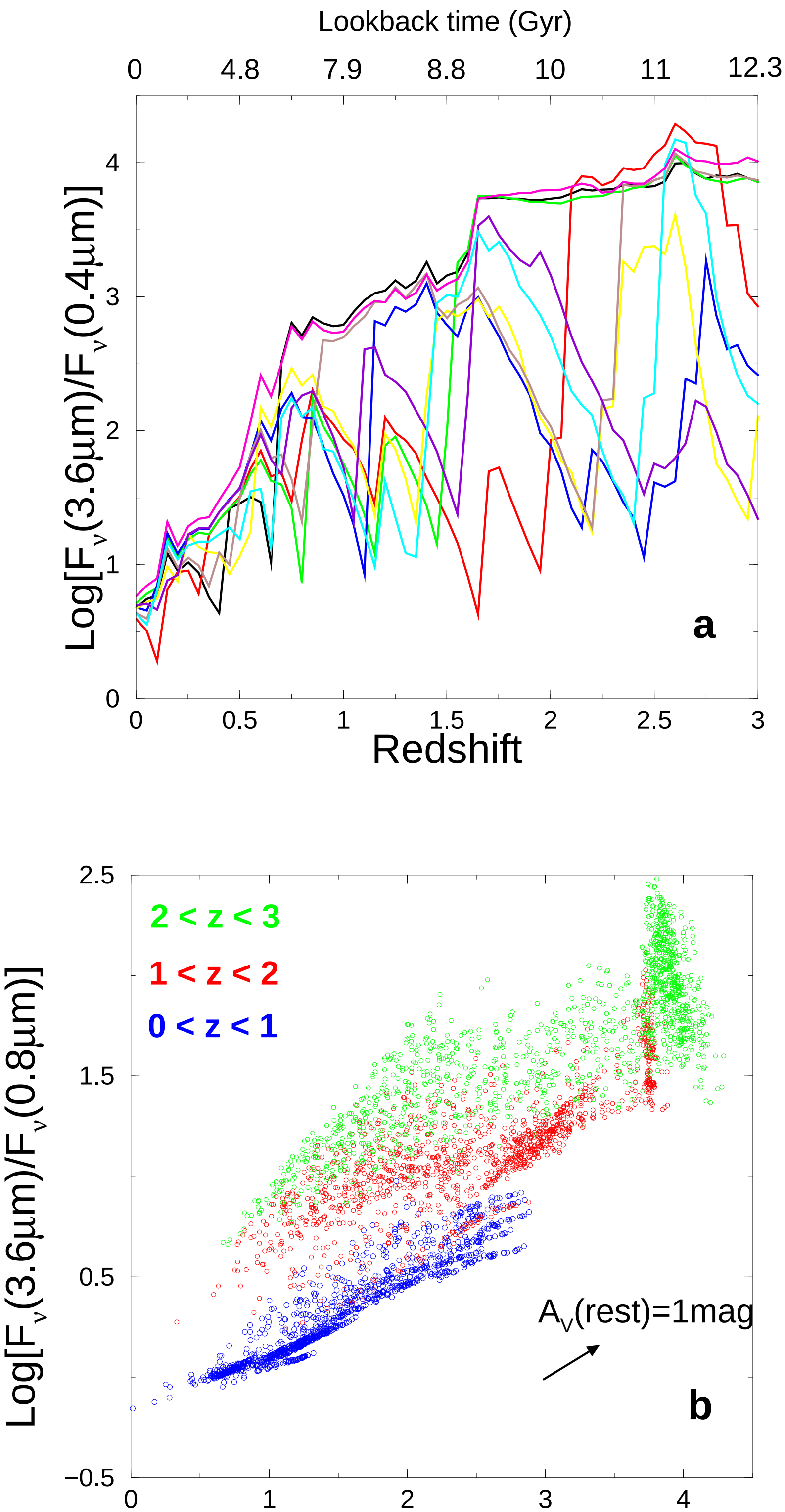

Figure 4: **(a)** Observed IRAC (3.6μ)m-to-optical color as a function of redshift for a random subset of spheroid histories. Each individual history is color coded. **(b)** Simulated colors from our bulge-building model using IRAC and optical bandpasses. An observed reddening vector is shown for a rest frame ($z = 0$) extinction $A_V = 1$ mag, and its length scales as $\approx (1 + z)$ for $z > 0$.

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