AN EVOLUTIONARY MODEL FOR SUBMILLIMETER GALAXIES

SUHANYA CHAKRABARTI,1,2 YESHE FENNER,† T. J. COX,1 LARS HERNQUIST,1 AND BARBARA A. WHITNEY

Received 2006 November 1; accepted 2008 July 7

ABSTRACT

We calculate multiwavelength spectral energy distributions (SEDs) from simulations of major galaxy mergers with black hole feedback that produce submillimeter bright galaxies (SMGs), using the self-consistent three-dimensional radiative transfer code RADISHE. These calculations allow us to predict multiwavelength correlations for this important class of galaxies. We review star formation rates, the time evolution of the 850 μm fluxes, along with the time evolution of the MBH–M* relation of the SMGs formed in the mergers. We reproduce correlations for local AGNs observed in Spitzer Space Telescope’s IRAC bands, and make definitive predictions for infrared X-ray correlations. Our dynamical approach allows us to directly correlate observed clustering in the data as seen in IRAC color-color plots with the relative amount of time the system spends in a region of color-color space. We also find that this clustering is positively correlated with the stars dominating in their contribution to the total bolometric luminosity. We compare our calculated SEDs to observations of SMGs and find good agreement. We introduce a simple, heuristic classification scheme which we present in terms of the LIR/LX ratios of these galaxies, which may be interpreted as an evolutionary scheme, as these galaxies evolve in LIR/LX while transiting from a X-ray underluminous infrared bright phase (class I, LIR/LX ≥ 100), through a quasar phase (class II, LIR/LX ∼ 25), to a merger remnant (class III, LIR/LX ≤ 10). We find that SMGs are a broader class of systems than starbursts or quasars, traversing the range from class I to class II systems.

Subject headings: galaxies: formation — infrared: galaxies — radiative transfer — stars: formation

Online material: color figures

1. INTRODUCTION

The luminous (LIR ≥ 1 × 1012 L⊙), high-redshift, dusty galaxies that were discovered in large numbers by the Submillimeter Common-User Bolometer Array (SCUBA), now designated as submillimeter galaxies (SMGs), generate a significant fraction of the cosmic energy output (Smail et al. 1997; Ivison et al. 1998; Blain et al. 2002). As such, SMGs are key cosmological players, believed to be responsible for more than half of the star formation at z ∼ 2 (Blain et al. 2002).

These systems have been studied in a diverse range of wavelengths, spanning the range from X-rays to radio wavelengths. UV/optical spectroscopic redshifts (Chapman et al. 2003b, 2005; Swinbank et al. 2004) yield a median redshift of z ∼ 2 for this population. The presence of AGNs in these systems has been confirmed in X-ray surveys (Alexander et al. 2005a, 2005b); however, the contribution of the AGNs to the bolometric luminosity remains unclear. The analysis of Borys et al. (2005) of rest-frame X-ray and near-IR data suggests that SMGs fall nearly two orders of magnitude below the local MBH–M* relation, when Eddington-limited accretion is assumed to calculate the black hole masses. HST imaging indicates that these are large irregular galaxies (Chapman et al. 2003a), with some preliminary evidence for extended starbursts (Chapman et al. 2004), assuming that the radio emission is taken to trace the starburst. Blain et al. (2004a) and Chapman et al. (2004) stress the need to understand the SEDs of these systems, specifically, in regards to ascertaining whether a population of hot SMGs, which would be undetected in current submillimeter surveys, would contribute significantly to the infrared emission of z ∼ 2 galaxies. The most direct observational probe of the rest-frame far-infrared of high-redshift submillimeter selected galaxies is the set of SHARC-2 350 μm observations of z ∼ 2 systems obtained by Kovač et al. (2006). CO observations indicate that these galaxies have large gas reservoirs (Mgas ∼ 1010–1011 M⊙; Greve et al. 2004; Neri et al. 2003). SMGs have also been studied through high-resolution (∼1″) millimeter imaging and CO observations (Genzel et al. 2003; Tacconi et al. 2006) to reveal large gas masses; Tacconi et al. (2006) infer from their observations that their sample of SMGs do not have extended starbursts and suggest that SMGs are likely to be scaled-up, more gas-rich versions of local ultraluminous infrared galaxies (ULIRGs), the dusty infrared-bright galaxies with L8 μm–1000 μm ∼ 1 × 1012 L⊙ discovered in large numbers by IRAS (Soifer et al. 1984; 1987). SMGs have been proposed as candidates for the progenitors of the most massive spheroids in the local universe (Lilly 1999). There is also some indication that SMGs are a clustered population (Blain et al. 2004b), with similar correlation lengths for SMGs and quasars (Croom et al. 2005). These recent intriguing set of observations have prompted the development of various models to fit the spectral energy distributions (SEDs) of SMGs, and to infer an evolutionary scheme for this important class of galaxies. On the interpretative end, Farrah et al. (2002) suggest, on the basis of axially symmetric radiative transfer calculations which incorporate a model of evolving H II regions, that the starburst dominates in its contribution to wavelengths longer than rest-frame far-IR. Rowan-Robinson (2000) finds that high-redshift hyperluminous infrared galaxies (HLIRGs) have star formation rates greater than 1000 M⊙ yr−1 and are candidates for primeval galaxies undergoing a burst of star formation, rather than merging systems. Efstathiou & Rowan-Robinson (2003) find that “cirrus” axisymmetric models, i.e., extended emission from dusty envelopes with low optical depths, better describe SCUBA sources, and that they may be more akin to optically selected high-redshift galaxies than obscured starbursting galaxies. Baugh et al. (2005) have been able to reproduce the observed galaxy number counts at 850 μm, assuming a top-heavy IMF within the context of a semianalytic prescription for galaxy evolution, coupled with the axisymmetric dust radiative transfer code developed by Silva et al. (1998).
High-resolution imaging of local ULIRGs has revealed the complex morphologies of these systems (Soifer et al. 2000; Goldader et al. 2002; Scoville et al. 2000), indicating a merger-driven origin. This scenario is supported by simulations demonstrating that tidal interactions during a major merger cause gas inflows by gravitational torques (e.g., Barnes & Hernquist 1991, 1996), leading to nuclear starbursts (e.g., Mihos & Hernquist 1994, 1996). A recent analysis of spectroscopic data in conjunction with high-resolution infrared imaging (Dasyra et al. 2006) indicates that the majority of ULIRGs are formed in nearly equal mass major mergers. Unless high-redshift ULIRGs are more quiescent than the local systems, it is unlikely that axisymmetric models will prove to be representative of SMGs. The complex dynamical behavior of merging galaxies has been modeled in numerical simulations incorporating feedback from central black holes (Springel et al. 2005a, 2005b; Di Matteo et al. 2005). Chakrabarti et al. (2007, hereafter C07) employed these simulations of major mergers with black hole and starburst-driven feedback (Cox et al. 2008) to calculate the infrared emission of local ULIRGs and LIRGs using a self-consistent fully three-dimensional radiative transfer code. These calculations reproduced observed trends such as the empirical warm-cold IRAS classification (de Grijs et al. 1985), wherein energetically active AGNs are found to be correlated with high $F_{25\mu m}/F_{60\mu m}$ colors ($F_{25\mu m}/F_{60\mu m} \gtrsim 0.2$), and demonstrated that these trends are directly driven by feedback processes.

We build on these recent developments here by calculating pan-chromatic SEDs, spanning optical to millimeter wavelengths, of simulations of gas-rich major mergers by using the self-consistent three-dimensional radiative transfer code RADISHE, which treats the scattering, absorption, and reemission of photons from dust grains, with the dust temperature calculated iteratively on the basis of radiative equilibrium (Chakrabarti & Whitney 2008) by using the Lucy temperature algorithm (Lucy 1999). We conduct a multiwavelength analysis of correlations from rest-frame near-infrared to submillimeter bands, as well as infrared X-ray correlations. We also compare our simulated SEDs with recent far-IR observations of SMGs by Kovacs et al. (2006) and to Spitzer observations by Pope et al. (2006). Our goal in this paper is to highlight the physical and dynamical basis for the multiwavelength correlations that we predict. In particular, our multiwavelength dynamical approach allows us to cast trends in color-color space directly in terms of color evolution as a function of time, or of color evolution as a function of the relative luminosities from the black hole and the stars.

There are some differences both in the hydrodynamical simulation parameters and in the radiative transfer modeling in this paper, as compared to that in C07. Firstly, C07 studied the far-IR evolution of the SED, and therefore made a simplifying assumption about the galactic distribution of dust. Since the far-IR SED is not significantly affected by the inclusion of dust in a diffuse phase of the ISM, C07 considered the effects of dust emission from the cold component of the ISM. Since we present and analyze pan-chromatic SEDs in this paper, we generalize this approach and also include dust in the diffuse component of the ISM. We also present inclination-dependent SEDs in this paper, as the shorter wavelengths generally vary significantly with viewing angle. Secondly, SMGs at $z \sim 2$ are more luminous than local ULIRGs by a factor of about 5 on average, and are also more massive (Chakrabarti & McKee 2008, hereafter CM08), although the light-to-mass ratios of local ULIRGs and $z \sim 2$ SMGs are similar. Therefore, the majority of the simulations in this paper are more massive, luminous systems than those discussed in C07, which was focused on local ULIRGs. We employ simulations of major mergers in both of these papers to describe the photometric time evolution of local ULIRGs (in C07) and SMGs (this paper). Bouche et al. (2007) suggest that dissipative major mergers are likely to have produced the SMG population as they have lower angular momenta and higher matter densities compared to the UV/optically selected population.

The organization of this paper is as follows. In §2, we review the merger simulations and the translation from the smooth particle hydrodynamics (SPH) information to the spatial grid that we use to do the radiative transfer calculations. In §3, we review our radiative transfer methodology and the dust model we have used, along with our adopted model for PAH emission. Section 4 presents our results, beginning in §4.1 which gives the star formation rates, the evolution of the $850\mu m$ fluxes, and the $M_{BH}-M_*$ relation for SMGs. In §4.2, we present the simulated IRAC color-color plot in the rest-frame, and explain the clustering in this plot. In §4.3, we make a number of predictions infrared X-ray correlations, which can be tested empirically by obtaining a large sample of observations in a narrow wavelength range. We present photo albums spanning the lifetime of SMGs during the active phase in §4.3. In §5, we compare our SEDs from the simulations to observed data, and present the IRAC color-color plot in the observed frame for galaxies at $z = 2$, and show a plot depicting the variation of the $850\mu m$ fluxes as a function of X-ray luminosity. We introduce a simple classification scheme for SMGs on the basis of the $L_{IR}/L_X$ ratios which also corresponds to an evolutionary scheme. We conclude in §6. The Appendices are devoted to an exploration of the effects of varying the dust composition, specifically, our inclusion of dust in the diffuse phase of the ISM, and to the dependence of the $850\mu m$ flux on simulation parameters.

2. MERGER SIMULATIONS

We employ the parallel TreeSPH code GADGET-2 (Springel 2005) to perform simulations of major mergers. The numerical implementation of a subresolution multiphase model of the ISM to describe star formation is developed in Springel & Hernquist (2003, hereafter SH03). Here, we briefly discuss the empirical motivation for the star formation prescription in GADGET-2, which we have not previously discussed in detail in C07. These simulations employ a Kennicutt-Schmidt density-dependent prescription to convert gas to stars (Kennicutt 1998; $S_{\text{gas}} \propto \Sigma_{\text{gas}}^{1.4}$). Systems that are the products of gas-rich mergers, such as ULIRGs and SMGs (Bouche et al. 2007; Krumholz & McKee 2005), are found to lie on the Kennicutt-Schmidt relation, only at higher gas surface densities than normal galaxies. The original work by Kennicutt included some infrared luminous galaxies which he found did fall on the Kennicutt-Schmidt relation. The recent work by Bouche et al. (2007) indicates that gas-rich major mergers that are heavily star-forming do obey a universal star formation law. The physical basis of such a law is still being debated. Krumholz & McKee (2005) find that this law can be produced by turbulence-driven star formation, while Shu et al. (2007) find that magnetically regulated star formation naturally produces this empirical correlation. It is beyond the scope of this paper to investigate this in detail; we merely make use of this empirically observed correlation to convert gas to stars as the resolution of the simulations is not sufficient to follow star formation internal to GMCs.

We have considered a diverse range of simulations in this paper, of varying virial mass and orbital inclination. We give a summary of the simulations analyzed in this paper in Table 1, including the virial mass of the two galaxies, the orbital orientation, which is denoted “h” for a coplanar merger, and “e” for an arbitrary inclination, the virial velocity, and the stellar mass near the peak
of the submillimeter bright phase. The names that we use to refer to the simulations along with names used in previous papers (i.e., Cox et al. 2006b; Hopkins et al. 2005) are given in parentheses. A description of orbital parameters, such as pericentric separations (which are typically taken to be of the virial radius) and orbital orientations, is given in Cox et al. (2006b). The orbital orientation denoted “e” corresponds to $\theta_1 = 30, \phi_1 = 60$ for the first disk, and $\theta_2 = -30, \phi_2 = 45$ for the second disk (also in Table 1 of Cox et al. 2006b). Simulations h226 and e226 are in all ways identical except for the initial orbital orientation (same for h320 and e320, etc.). Simulations e160 and h160 are identical except for initial orbital orientation and initial gas fraction (which are 40% and 100%, respectively); although the initial gas fractions of most of these simulations are large, the gas fractions during the SMG phase are ~30% and agree with observations (Tacconi et al. 2008). The inclusion of continued infall of gas from the IGM (which is not included in these simulations of binary mergers) would likely require less extreme initial gas fractions to produce infrared bright galaxies. We discuss later that differences in the initial orbital parameters of the progenitors, such as pericentric separation or orbital inclination, do not significantly affect the times close to (and beyond) the final merger of the two black holes—which is the infrared luminous phase that we study in this paper. The virial mass (and corresponding stellar and gas mass) does influence the infrared properties toward the late stages of the merger.

3. RADIATIVE TRANSFER METHODOLOGY

We use the self-consistent three-dimensional Monte Carlo radiative equilibrium code RADISHE (Chakrabarti & Whitney 2008, hereafter CW08) to calculate the emergent SEDs and images from the merger simulations as a function of evolutionary state. This code incorporates the Monte Carlo radiative equilibrium algorithm developed by Lucy (1999) to solve for the equilibrium temperature of the dust grains. The radiative transfer methodology and the relevant mathematical formalism has been presented in § 2 of CW08. We refer the interested reader to our paper and simply review the basic points here. An essential step in self-consistently calculating the emergent SED from dust envelopes that are optically thick to their own reprocessed radiation is to calculate the dust temperature on the basis of radiative equilibrium, which is the condition of energy balance that guarantees that the energy absorbed, $\int \kappa_\nu d\nu$, is equal to the energy emitted, $\int \kappa_\nu B_\nu(T) d\nu$, where $B_\nu(T)$ is a function of temperature on the spatial grid, and the mean intensity is given by the sum of path lengths of photons traversing grid cells (eq. [12] in Lucy 1999). When the envelope is optically thin to its own reprocessed radiation, this condition of energy balance reduces to a local calculation of the dust temperature. More generally, this integral equation must be solved iteratively, which we have done following Lucy (1999); in simple geometries, an analytic calculation is feasible (Chakrabarti & McKee 2005). This code is based on the radiative equilibrium code described in Whitney et al. (2003), and solves the radiation transfer equation exactly including non-isotropic scattering, polarization, and a self-consistent calculation of the dust temperature (Lucy 1999) in three-dimensional geometries.

Our assumptions about the distribution of dust in the ISM and its effects on the SED, as well as a direct demonstration that the local absorption of UV light in stellar birth clouds does not lead to a significant change in the emergent SEDs in ULIRGs, are given in Appendix A. The reason why local absorption of UV photons in stellar birth clouds is not of significant importance in ULIRGs is that the large global obscuration is responsible for nearly all of reprocessed infrared emission. We justify this point in Appendix A through a direct calculation—we include this effect for star clusters with ages of 1 and 10 Myr; for the case we consider, stars with ages less than 10 million years contribute a sizable fraction to the total luminosity (about 20%), but there is little change in the emergent SED when this effect is included. Our prescription here is simple, and amounts to replacing the intrinsic UV/optical spectrum of young star particles with the emergent infrared SED of a star cluster with $L/M = 20 \ L_\odot \ M_\odot^{-1}$ and $\Sigma = 1 \ g \ cm^{-2}$, using the analytic methodology of Chakrabarti & McKee (2005) to calculate the emergent infrared SED of such a star cluster. Since the hydrodynamical simulations do not have enough resolution to resolve star clusters and therefore do not include the obscuring dust envelope within star clusters, our approach is similar to a subgrid specification of the local absorption of UV photons in stellar birth clouds. In principle, our approach can be improved further by including a time dependence (rather than the step function—like approach we have adopted here, i.e., either including this effect for stars of some age or not at all) as described in Dopita et al. (2005). This effect may alter the emergent SEDs of more translucent systems if a sizable fraction of the luminosity comes from young stars. However, it does not significantly change the emergent SEDs in ULIRGs due to the large global obscurations, particularly in the nuclear regions where the starburst occurs.

The intrinsic AGN continuum spectrum is modeled using the Hopkins et al. (2007, hereafter HRH07) spectrum, which is based on optical through hard X-ray observations (Elvis et al. 1994; Georgie et al. 1998; Perola et al. 2002; Telfer et al. 2002; Ueda et al. 2003; Vignali et al. 2003), with a reflection component generated by the PEXRAV model (Magdziarz & Zdziarski 1995). The HRH07 spectrum is similar to that developed by Marconi et al. (2004), but it is more representative of the shapes of typical observed quasars; it includes a template for the observed “hot dust” component longward of 1 $\mu$m. Since the merger simulations typically have a gravitational softening length of ~50 pc, they do not resolve the inner regions which produce the “hot dust” ($T \gtrsim 1000 \ K$) in observed AGN spectra. This template, which includes this hot dust component, is used as a proxy for the dust emission close to the AGN. The differences in emergent spectra with and without the use of this template have been discussed in CW08. The clump size and mass distribution is sampled from a probability distribution function that is motivated by observations of GMCs (CW08), for a turbulent to thermal pressure ratio of 100 for the cold clumps. Increasing the turbulent to thermal pressure ratio increases the volume filling fraction of the dust fraction (by making the clumps puffier) and thereby lowers the mid-IR flux. As pointed out by C07, this value for the turbulent to thermal pressure ratio is motivated by measurements of the velocity dispersion and thermal sound speed in protostellar

| Simulation    | $M_{d,J}$ ($M_\odot$) | Orbital Orientation | $V_{vi}$ (km s$^{-1}$) | $M_{d,IR peak}$ |
|---------------|-----------------------|---------------------|------------------------|-----------------|
| e160 (vc3e)   | $2.7 \times 10^{12}$  | e                   | 160                    | $1 \times 10^{11}$ |
| h160 (A3)     | $2.7 \times 10^{12}$  | h                   | 160                    | $1 \times 10^{11}$ |
| h226 (A4)     | $7.7 \times 10^{12}$  | h                   | 226                    | $3 \times 10^{11}$ |
| h320 (A5)     | $2.2 \times 10^{13}$  | h                   | 320                    | $9.9 \times 10^{11}$ |
| h500 (A6)     | $8.3 \times 10^{13}$  | h                   | 500                    | $4.0 \times 10^{12}$ |
| e226 (A4e)    | $7.7 \times 10^{12}$  | e                   | 226                    | $3 \times 10^{11}$ |
| e320 (A5e)    | $2.2 \times 10^{13}$  | e                   | 320                    | $9.4 \times 10^{11}$ |
| e500 (A6e)    | $8.3 \times 10^{13}$  | e                   | 500                    | $3.9 \times 10^{12}$ |
regions and simple models of GMCs. We have performed Starburst99 calculations (Leitherer et al. 1999; Vazquez & Leitherer 2005) to calculate the stellar spectrum and bolometric stellar luminosity, taking as input the age, mass, and metallicity of the stars from the simulations, for both the Kroupa and Salpeter IMFs.

Li et al. (2008) seem to attribute the shape of the near- and mid-IR SED to the resolution of the grid. As the gravitational softening length in the simulations is ~50 pc, we do not see that additional refinement in finer scales is necessary, and our resolution studies confirm this. Moreover, our use of the Lucy temperature calculation algorithm allows for greater speed and accuracy (in contrast to their use of the Bjorkman & Wood [2001] algorithm). We find, therefore, that Li et al. (2008) have overemphasized the resolution aspect of their calculation. As discussed in the Appendix and in Chakrabarti & Whitney (2008), the shape of the near- and mid-IR SED is governed in these calculations primarily by the use of the HRH spectrum and our assumptions about the dust-to-gas ratios in the dense and diffuse phases of the ISM. C07 and Chakrabarti & McKee (2005) explained the shape of the far-IR SED in terms of $L/M$ and $\Sigma$.

We use a grain model consistent with the Weingartner & Draine (2001, hereafter WD01) $R_F = 5.5$ case A dust opacity model, both with and without the addition of ice mantles. For simplicity, we ignore detailed effects related to the emissivity dependence on individual grain sizes. As such, our grain emissivities are simply a function of wavelength. An improvement that is likely to be relevant for nonthermal effects such as PAH emission is the incorporation of a grain size distribution and resultant temperature calculation for different grain sizes. While we calculate the equilibrium dust temperature self-consistently in three-dimensional geometries, we do so for an average grain size distribution that is consistent with the WD01 model. This approach has been found to be a good approximation for equilibrium dust temperature calculations (Wolf 2003; Carciofi et al. 2004). The reason for this is that differently sized grains have similar optical properties at long wavelengths at which the dust reprocesses the starlight; thus, an approximate invariance in the emergent dust thermal SEDs can be expected (Ivezic & Elitzur 1997). As noted above, we make the assumption of radiative equilibrium. This assumption may be problematic shortward of the MIPS 70 $\mu$m band, particularly in the IRAC and IRS bands, where strong PAH lines have been detected from infrared bright galaxies (Armus et al. 2007; Yan et al. 2007).

The inclusion of ice mantles (which lead to an effective increase in the opacity of ~2 for $T \approx 100$ K above which ices sublimate; e.g., Pollack et al. 1994) is motivated by spectroscopic studies that have identified ice spectral features in protostellar environments and in dusty galaxies (Allamandola et al. 1992; Spoon et al. 2002). The mass fraction of dust is equal to $1/105.1$ for solar abundances (WD01). WD01’s models have been shown to reproduce the observed extinction curves for the Milky Way, as well as regions of low metallicity, such as the LMC and the SMC. The opacity normalization per gram of dust, $\kappa_{\lambda_{0}}$, is equal to 0.276 for $\lambda_{0} = 100$ $\mu$m, where $\delta$ is the dust-to-gas ratio relative to solar, which we take to be unity. We increase this normalization by a factor of 2 to account for ice mantles. We summarize our dust model parameters in Table 2. Dunne & Eales (2001) and Klaas et al. (2001) found that the dust-to-gas ratio for a large sample of ULIRGs is comparable to Milky Way values, when they fit two-temperature blackbodies to the far-IR SEDs. Previous work, based on fitting single-temperature blackbodies, had found lower dust-to-gas ratios (Dunne et al. 2000) by a factor of 2. Furthermore, this dust model has been used successfully in fitting the observed SEDs of ULIRGs and SMGs by Chakrabarti & McKee (2005, 2008). As discussed in Appendix A, for dust in the diffuse phase of the ISM, we adopt a fiducial dust-to-gas ratio that is 1/10 of that in the cold phase. We will perform a larger parameter study in the future to explore the effects of changing the dust opacity curve, as well as a more detailed treatment of the assumptions regarding the obscuration around young star clusters, as discussed in Appendix A.

We adopt a phenomenological model of PAH emission here. If the UV luminosity is of order 1/10th or greater of the total luminosity, then we add on an observed PAH template (adopted from Dopita et al. 2005) to the SED, where the PAH strength is scaled to the 200 $\mu$m flux as in Dale & Helou (2002). We do not here incorporate changes in the PAH abundance due to varying radiation fields, or treat the process of PAH emission self-consistently. As noted before, we do not resolve regions close to the AGN, and employ a spectral template (HRH07) to represent dust emission that emanates from scales close to the AGN. Our approximation of scaling the PAH strength to the 200 $\mu$m flux is motivated by Dale & Helou’s (2002) finding that when galaxy model spectra are normalized to the 6.2 $\mu$m feature, the 200 $\mu$m fluxes of different galaxies are very similar, which may be due to star formation powering both of these parts of the SED. The contribution of PAH features to wavelengths greater than 20 $\mu$m is not statistically clear (Smith et al. 2007), and the considerably larger extinctions in SMGs may well reduce the source of UV photons needed to excite PAH molecules in SMGs even at lower wavelengths. The self-consistent treatment of PAH emission in a three-dimensional radiative transfer code is beyond the scope of the paper. We do find (see § 4) that use of this template does recover observed correlations in the IRAC bands. We present these preliminary results of a composite PAH and continuum SED with the intent of understanding if the use of a PAH template can recover observed correlations. In a forthcoming work, we treat PAH emission self-consistently in RADISHE.

4. RESULTS AND ANALYSIS

We plot in Figure 1 the star formation rates for the simulations analyzed in this paper. Inferred star formation rates of SMGs vary from the high star formation rates of cirrus models, $SFR \gtrsim 1000 M_\odot$ yr$^{-1}$ (Efstathiou & Rowan-Robinson 2003; Rowan-Robinson 2000), to about $500 M_\odot$ yr$^{-1}$ if a factor of 2 is used to account for the AGN contribution to the infrared luminosity, along with the relation of Kennicutt (1998) for the star formation rate and the infrared luminosity (Genzel et al. 2003); inferring star formation rates without including the contribution of the AGN leads to star formation of the order of several thousand solar masses per year (Ivison et al. 1998). In these simulations, during the active phase, the star formation rates are on average $\sim 500–1000 M_\odot$ yr$^{-1}$ and produce bright SMGs as we discuss below. We show the variation of the star formation rate (and other quantities) in terms of the time after the final merger of the two galaxies. Large virial and stellar masses have been inferred for the $z \sim 2$ SMG population (Borys et al. 2005; Nesvadba et al. 2007; Tacconi et al. 2008), and we thus focus on simulations
with large virial masses \((\sim 10^{13} M_\odot)\) and correspondingly large stellar masses \((\sim \text{few } 10^{11} - 10^{12} M_\odot)\).

We show in Figure 2 the observed 850 \(\mu\)m flux as a function of time for e160, e226, and e320, which span the range from virial masses from \(2 \times 10^{12} - 2 \times 10^{13} M_\odot\). The 850 \(\mu\)m flux is shown for galaxies at a luminosity distance of \(D_L = 15.5\) Gpc (this corresponds to the rest-frame 283 \(\mu\)m flux at \(z = 2\)). SMGs are an empirically defined class of galaxies, based on the observed 850 \(\mu\)m flux; systems with observed \(F_{850 \mu m} \gtrsim 1\) mJy are designated as submillimeter bright (Ivison et al. 2000; Blain et al. 2002). The horizontal line demarcates this criterion \((F_{850 \mu m} \gtrsim 1\) mJy) on our flux versus time plots. (This empirical definition of submillimeter bright may well change owing to improved sensitivity of future submillimeter surveys, i.e., SCUBA-2.)

As is clear, the peak 850 \(\mu\)m flux increases as a function of virial mass. Dependence of the submillimeter flux on other parameters, such as orbital inclination, assumptions about the dust opacity, are discussed in Appendix B. The more massive galaxies show a more rapid and pronounced decline in their submillimeter flux as a function of time as these systems are losing gas content both owing to AGN feedback clearing out the dust and gas in a more violent fashion, as well as to forming stars at a faster rate. In general, much of (\(~80\%) the gas is converted to stars, with \(~10\%) converted to a hot gaseous halo (Cox et al. 2006b), and \(~5\%) ejected due to AGN feedback. C07 and Cox et al. (2008) note that the coincident increase in luminosity of the AGN close to the main feedback phase, which lowers the dust column, is responsible for “warm” colors, in contrast to simulations with only starburst feedback, which have a more gradual dispersal of the obscuring material that is not coincident in time with the peak luminosity of the galaxy.

We show in Figure 3 the evolution of \(M_{BH}/M_\odot\) as a function of time for e226 (medium gray line), e320 (dark gray line), and e500 (light gray lines). The dotted lines correspond to deriving the black hole mass for Eddington limited accretion. This shows that deriving black hole masses under the assumption of Eddington-limited accretion underestimates the black hole masses by a factor of \(~5\) during the SMG phase.
A. Borys et al. (2005) discuss the relationship between the simulated galaxies spending most of their time in that phase. The SMG phase for the simulations shown in Figure 3 occurs close to the final coalescence of the galaxies ($t \sim 0$); such systems would indeed lie below the local relation, but by only 2 orders of magnitude. We show the change in $M_{\text{BH}}/M_*$ when we obtain the black hole masses assuming Eddington-limited growth (Fig. 3, dotted lines), which would then lead to the appearance of such objects falling about 2 orders of magnitude below the local relation, while we find that the black hole masses would grow perhaps by a factor of $\sim 5$ between the SMG phase at $z = 2$ and the present day.

4.1. IRAC Correlations

We plot in Figure 4 an IRAC color-color plot in the rest frame over 200 viewing angles for each of our simulations. Lacy et al. (2004) identified AGNs as the sources that fall within the dashed lines. We recover the general trends of the observed IRAC color-color plot from Spitzer Space Telescope’s First Look Survey (FLS), namely, the clustering of the fluxes in the lower left-hand corner of the plot (both colors being bluer), as well as a small fraction of these sources falling on the redder sequence. Specifically, of the 16,000 objects shown in the Lacy plot, 2000 are likely to contain AGNs, while 20 were robustly identified to be obscured AGNs. Approximately, 15% of the simulated colors fall in the energetically active AGN region, with the majority of the simulated colors clustering in the bluer region of the plot.

The power of the dynamical approach afforded by calculating fluxes from the simulations is that we can unfold this color-color plot to a color versus time plot for each axis, as shown in the following Figure 5. As this plot shows, the clustering that is present in the observed color-color plot, which we reproduce also in the simulation IRAC color-color plot, is naturally explained in our models by the SMG spending more of its lifetime in that region of color space. The low $F_{\text{3.6}}/F_{\text{4.5}}$ and $F_{\text{5.8}}/F_{\text{3.6}}$ colors correspond to the Rayleigh-Jeans tail of attenuated starlight (modulated by the albedo) influencing the IRAC colors. It is a simple exercise to show that the Rayleigh-Jeans tail of stellar spectra leads to $\log (F_{\text{4.5}}/F_{\text{3.6}})$ and $\log (F_{\text{5.8}}/F_{\text{3.6}})$ roughly of order $-0.5$, independent of the details of the stellar spectrum. Figure 6 plots the IRAC colors as a function of $L_{\text{BH}}/L_*$; this shows that if the IRAC colors fall within the dashed region demarcated by Lacy et al. (2004), the source is certainly an energetically active AGN, i.e., the bolometric luminosity from the black hole is greater than or comparable to the luminosity from the stars. However, there are also cases when the AGN’s luminosity is greater than or comparable to the stars, and yet it is not in the AGN-demarcated region of color-color space. For instance, most of the points which have blue colors in $F_{\text{3.6}}/F_{\text{4.5}}$ and red colors in $F_{\text{4.5}}/F_{\text{3.6}}$ do have $L_{\text{BH}} \gtrsim L_*$, as well as a few of the points that have blue $F_{\text{3.6}}/F_{\text{4.5}}$ and blue $F_{\text{4.5}}/F_{\text{3.6}}$ colors. (For the most part, however, sources that have blue colors for both axes are dominated by the stellar luminosity.) This variation seems to owe to the effects of larger and more extended starbursts in some of the coplanar mergers. Therefore, while we confirm the Lacy et al. (2004) IRAC correlations in general, our interpretation of the blue-red plume, as well as sources that lie close to the demarcating line for AGNs, is different from their analysis. We suggest that some of these sources may also have energetically active AGNs, which could be detected in deep X-ray surveys.

![Fig. 4.—Correlations in rest-frame IRAC bands (for the continuum), shown for all the simulations analyzed in this paper. Dashed lines demarcate color criteria to pick out obscured AGN sample by Lacy et al. (2004).](image1)

![Fig. 5.—Rest-frame IRAC color-color plots for the continuum as a function of time. The clustering in the lower left-hand corner of the IRAC color-color plot owes to the simulated galaxies spending most of their time in that phase.](image2)
We emphasize that this interpretation of the IRAC color-color plot is most appropriate when viewed in the rest frame, as the clustering properties and relative fraction in the AGN demarcated region can then be directly correlated with dynamical properties of these galaxies, such as the relative amount of time the system spends in some region of color-color space and the relative contribution from the black hole luminosity. One can interpret the FLS IRAC color-color plot roughly in the manner outlined above as well since Lacy et al. (2004) note that the median photometric redshift of their candidate AGN is $z \approx 0.3$. We discuss later in § 4.5 that the continuum is not as sensitive to redshifting the SED as the PAH features; hence, the continuum in the observed frame is quite similar (for a range of redshifts at least, as we discuss in § 5) to the rest-frame color-color plot. Nonetheless, the dynamical interpretation of trends in color-color space is most easily understood in terms of rest-frame quantities.

The recent, comprehensive work by Barmby et al. (2006) corroborates our suggestion regarding the blue-red plume containing an energetically active AGN. Specifically, Barmby et al. (2006) find that the infrared properties of X-ray sources in the Extended Groth Strip are very diverse, about 40% of the X-ray detected sources have red power-law SEDs in the 3.6–8.0 μm IRAC bands, while another 40% have blue SEDs. Thus, while the presence of sources in the AGN demarcated region in the IRAC color-color plot is a sure sign of an energetically active AGN, the converse is not necessarily true (as Fig. 6 has shown). The diversity of infrared properties of X-ray detected sources is further highlighted by Rigby et al. (2004), who found that X-ray hard AGNs are not preferentially infrared brighter; Alonso-Herrero et al. (2004) found that sources in the Lockman Hole with similar selection criteria have a variety of optical/IR spectral types. Therefore, while AGN identification using the IRAC color-color selection is generally effective, it may undercount the number of energetically active AGNs as it would miss the bluer region.

We show in Figure 7 our simulated IRAC color-color plot with inclusion of our phenomenological model of PAH emission. The PAH region, as shown in this figure, is qualitatively in agreement with the results of Sajina et al. (2005), who use a combined template of stellar emission, a power law for the mid-IR spectrum, and a PAH template to simulate an IRAC color-color plot. Interestingly, our color-color plot for the continuum (as shown in Fig. 4)—which is derived from self-consistent three-dimensional radiative transfer solutions—is in better agreement with the observed FLS IRAC color-color plot shown in Lacy et al. (2004) than the results of Sajina et al. (2005). Lacy et al. (2004) note that the median photometric redshift of the candidate AGN is $z \approx 0.3$ in the FLS color-color plot. The location of the PAH region in the color-color plot is a sensitive function of redshift. While in the rest frame the PAH region extends into (and bends toward) the AGN demarcated region (as we have shown here), redshifting the PAH template to $z \approx 0.1$ causes the PAH region to bend into the bluer region—resulting in the appearance of the “bunny-ear” shape seen in FLS IRAC color-color plot, as has been noted by Sajina et al. (2005). We show later in § 5 an IRAC color-color plot in the observed frame for galaxies at a range of redshifts, $z \approx 0.3$–2, which do indeed result in the characteristic “bunny-ear” shape for the $z = 0.3$ sample.

4.2. Infrared X-Ray Correlations

A large population of obscured AGNs is discerned from the hard X-ray background (Comastri et al. 1995); these systems would reradiate a significant fraction of their luminosity into the infrared, in principle explaining the spectral shape of the X-ray background. Therefore, infrared X-ray correlations hold promise...
The hard X-ray luminosity. There is a large scatter at low X-ray and IR luminosities. This makes intuitive sense; in our model, low X-ray luminosities correspond to the pre- and post-accretion phase, before (and after) the black hole has become energetically active (active meaning dominant in its contribution to the total bolometric luminosity; this case is essentially analogous to a central source of luminosity powering the infrared radiation. Hence, there should be a correlation between the luminosity of the central source and the reprocessed radiation in this phase. We have checked that performing the radiative transfer calculation with the black hole as the single source of luminosity gives a very similar correlation between \( L_{\text{IR}} \) and \( L_X \) as when the galaxy's bolometric luminosity is dominated by the black hole's luminosity. These systems, at their peak infrared luminosity, usually exceed ULIRG, and sometimes HLRG \( (L_{\text{IR}} \gtrsim 10^{13} L_\odot) \) luminosities. On average, the X-ray luminosities are of order \( 10^{10} L_\odot \), although there are a few on the very bright X-ray end \( (L_X \sim 10^{11}-10^{12} L_\odot) \) which correspond to the phase when the black hole dominates the bolometric luminosity.

Alexander et al. (2005a) find that the X-ray luminosity of their SCUBA selected sample is \( \sim 10^{11} L_\odot \), with only four in their sample exceeding \( 10^{11} L_\odot \). Alexander et al. (2005a) use the locally observed radio far-IR correlation to find that the X-ray luminosity is about 250 times lower than the infrared luminosity, whereas we find that it is typically \( \sim 100 \) times lower. The radio far-IR correlation has considerable scatter in luminous galaxies (Sadler et al. 2002), and its extrapolation to high redshifts is uncertain. As such, this discrepancy may in part owe to the fact that using the radio far-IR correlation underpredicts the infrared luminosity, since the contribution from the black hole has not been taken into account. Another possibility is that (part of) their X-ray sample is Compton thick, and hence has higher intrinsic luminosities than have been accounted for. Multiwavelength infrared observations are needed to observationally derive the rest-frame infrared luminosities to test our prediction.

The 70 \( \mu \)m luminosity displays the same behavior as the infrared luminosity (Fig. 8, middle); the relation between the 70 \( \mu \)m luminosity and hard X-ray luminosity is given by \( L_{70,\mu m} = 40L_X \). Figure 8 (bottom) shows that a similar behavior for the rest-frame 24 \( \mu \)m flux, with the brightest 24 \( \mu \)m objects being strongly correlated with the hard X-ray luminosity. There is nearly an order of magnitude of scatter relative to this line; the best-fit line going through the SMG data is given by \( L_{25,\mu m} = 10L_X \). These correlations are predictions from this model, which can be directly tested by combining far-IR and X-ray data at comparable sensitivities for large samples of SMGs. This should be made possible by the upcoming Herschel mission. Source-stacking analysis may make testing this prediction feasible, at least in a statistical sense, by using existing MIPS data. We explore infrared X-ray correlations for the IRAC bands in a future work. These shorter wavelengths will likely be influenced by PAH emission, a process which we have not yet treated self-consistently. Our use of a PAH template does reproduce observed correlations for the IRAC color-color plot. There is a great diversity in the current observations of infrared bright systems at these shorter wavelengths. Yan et al. (2005) find that 60% of their sources between redshifts of 1.8 and 2.6 have weak or no PAH emission, while about half have prominent silicate absorption lines. Both PAH spectral features and non–power-law continuum features will heighten the relative scatter for IRAC X-ray correlations, as compared to the far-IR X-ray correlations. Rigby et al. (2004) emphasize the diversity of 24 \( \mu \)m properties of X-ray selected AGNs, even in a narrow redshift slice \( (z \sim 0.7) \). They do see some indication of the ratio of the 24 \( \mu \)m to X-ray luminosity increasing with X-ray hardness for their subsample at \( z \sim 0.7 \), but there is scatter even in this subsample.
4.3. Photo Albums of the Lifetimes of SMGs

We present photo albums of the time evolution of the surface brightness in the observed 3.6 μm band, as well as the 450 μm band during the lifetime of three SMGs from our sample. We adopt a luminosity distance of 15.5 Gpc corresponding to \( z = 2 \) (\( \Omega_M = 0.3, \Omega_\Lambda = 0.7, H_0 = 70 \)) in these figures and take into account the instrumental angular resolution, convolving the images with a Gaussian point-spread function. Our goal here is to use these images as a visual aid in contrasting the time evolution of the surface brightness and morphologies of three SMGs of differing orbital inclination and progenitor redshift during their lifetimes.

Figure 9 shows a coplanar merger (h320) just slightly before the final merger of the two galaxies (left), to close to the main phase of AGN feedback (middle), to the final remnant (right). Figure 10 shows the corresponding images in the observed 450 μm band at the same times. The galaxy becomes brighter in the IRAC bands as it is becoming progressively fainter in the longer wavelength SCUBA band. This simply reflects the time variation of the fluxes; during the course of the simulation, as feedback from the AGN and continued star formation lower the amount of dust and gas, more of the emitted energy (the SED) shifts to shorter wavelengths, and there is correspondingly less emission at longer wavelengths. This trend would be seen also in surface brightness maps of the CO emission which probe the cooler regions of the envelope. Another point of note is that this coplanar merger has a disklike morphology, while the non-coplanar merger, shown in the following Figures 11 and 12, is more extended and non-disklike. However, it shows the same time evolution of the surface brightness: the brightness in the IRAC bands increases as the brightness in the SCUBA bands decreases as more of the emitted energy shifts to shorter wavelengths.

Chapman et al. (2003a) obtained HST images of about a dozen SMGs (\( z \sim 2 \)), and found that the morphologies were irregular and complex, suggestive of a merger origin. Chapman et al. (2004) compared optical and radio imaging of this sample, and using the radio as a tracer of the star-forming regions, argued for extended (about 10 kpc, but not much larger), obscured starbursts in about 70% of their sample, while in the rest of the sample, the radio extends to about 1 kpc. We note also that Genzel et al. (2003) studied a bright, lensed SMG at \( z = 2.8 \) to find a rotation velocity in excess of 400 km s\(^{-1}\), and millimeter emission in a disklike structure extending to about 10 kpc. These properties seem to be akin to our h320 coplanar merger. It is important to note here that a disklike image is a natural outcome of coplanar mergers (although such a orbital inclination is expected to be rare), i.e., the appearance of a disklike structure does not imply that the system had not undergone a major merger in the past. While there have been a number of recent papers (Pope et al. 2006; Iono et al. 2006) reporting high-resolution imaging of SMGs, detailed modeling of individual sources requires kinematic information along the lines obtained by Genzel et al. (2006) for a \( z \sim 3 \).
optically bright galaxy inferred to have a star formation rate of $\sim 100 M_\odot \text{ yr}^{-1}$ and a circular velocity of $\sim 230 \text{ km s}^{-1}$.

5. DISCUSSION

In comparing our predictions to observed data, there are several important points of note. First, we have depicted the IRAC and infrared X-ray correlations in the rest frame, which leads to a clear dynamical interpretation, as we have discussed previously. To test these predictions will require a large number of observations in a narrow redshift slice. Second, in comparing the 850 $\mu$m fluxes (which have been shown at $z = 2$, unless otherwise noted) to observations, it will be necessary to disentangle the effects of lensing, and of multiple counterparts contributing to the wide SCUBA field 850 $\mu$m flux. Moreover, a detailed study of current observational biases is needed. We defer this study to a future paper. Here, we point out a few basic observational comparisons: the IRAC color-color plot for galaxies placed at $z = 0.3–2$ in the observed frame; the time-evolution of a rest-frame SED; a comparison of our SEDs to recent data obtained by Kovacs et al. (2006) and Pope et al. (2006); and the 850 $\mu$m flux (shown at $z = 2$) as function of the ratio of black hole luminosity to total luminosity, and as a function of the X-ray luminosity.

SCUBA observations place constraints on the product of the dust mass and the dust temperature for SMGs by measuring the long-wavelength 850 $\mu$m flux, while Spitzer observations for some sources have been able to discern the presence of AGNs from power-law mid-IR SEDs (Pope et al. 2006; Rigby et al. 2004) and infer stellar masses from the near-IR SED (Borys et al. 2005). Figure 13 depicts data from Pope et al. (2006) of a X-ray bright SMG with a power-law mid-IR slope, compared to our calculated SED of the h320 simulation during the quasar phase, shown here over 200 viewing angles. However, without far-infrared measurements close to the peak of the SED, the total luminosity is uncertain, and the dust mass and temperature cannot be derived independently. In Figure 14, we compare the SEDs from the simulations h160, e226, e320, and e500 during the sub-millimeter bright phase to 350 $\mu$m data obtained by Kovacs et al. (2006) and find reasonable agreement. Kovacs et al. (2006) found that inferred blackbody dust temperatures of SMGs are $\sim 35 \text{ K}$, dust-to-gas mass ratios are comparable to local ULIRGs, and median luminosities are $\sim 5 \times 10^{12} L_\odot$. CM08 used an analytic self-consistent radiative transfer solution, which allows for a range of temperatures (rather than a single temperature), to fit the data from Kovacs et al. (2006) and found similar luminosities (slightly lower since they do not make the blackbody assumption) and masses; they also inferred the size of the dust-emitting region from the SED to find sizes of $\sim 10 \text{ kpc}$. Far-IR photometric measurements can also be used to obtain photometric redshifts (CM08) to an average accuracy of 10%. Future instruments like Herschel should be able to obtain large samples of far-IR measurements of $z \sim 2$ SMGs to build photometric templates [either in terms of dust temperature as in Kovacs et al. (2006) or in terms of the
light-to-mass ratio \((L/M)\) as in CM08] for use in inferring photometric redshifts of high-redshift dusty galaxies.

In these simulations, the brighter SMGs \(F_{850,\mu m} \gtrsim 1\) mJy at \(z \sim 2\) have nonnegligible \((L_{BH} \gtrsim 0.3L_{tot})\) contribution from the black hole to the total bolometric luminosity. Kovacs et al. (2006) use the radio far-infrared correlation to find that the SMGs in their sample would not have a significant contribution from the black hole luminosity. Their sample is biased toward radio-loud sources and does not include radio-quiet AGNs that would contribute to the far-infrared luminosity, increasing the derived \(q_L\) parameter, which is a measure of the far-infrared to radio luminosity. To better quantify our prediction for the variation of the 850 \(\mu m\) fluxes as a function of the ratio of black hole luminosity to the total bolometric luminosity, we show in Figures 15 and 16 the 850 \(\mu m\) flux as a function of the ratio of the black hole luminosity to the total bolometric luminosity and as a function of the X-ray luminosity. Figure 16 shows that there is a general trend for the 850 \(\mu m\) flux to increase as a function of the ratio of the black hole luminosity to the total bolometric luminosity. The brighter SMGs which have low \(L_{BH}/L_{tot}\) are the more massive systems. A significant caveat to interpreting observations, however, is the Compton-thick population, which the current simulations cannot model in detail.

We show in Figure 17 the IRAC color-color plot in the observed frame for simulations placed at \(z = 0.3, 1,\) and 2. The PAH spectral features redshift out of the IRAC bands by \(z \sim 0.5\), and the relative increase in \(L_{8,\mu m}/L_{4.5,\mu m}\) for energetically active AGNs also can no longer be seen. However, the transition from a roughly spherical distribution of colors for low-redshift objects to a flattened elliptical distribution of colors for \(z \sim 2\) objects may be useful for interpreting observations. As mentioned previously, the \(z = 0.3\) IRAC color-color plot displays the characteristic “bunny-ear” shape seen in the observed FLS color-color plot. We show the \(z = 0.3\) case here as Lacy et al. (2004) note that the median photometric redshift of their candidate AGN is \(\sim 0.3\). This contrasts with the rest-frame IRAC color-color plot shown in Figure 7 primarily owing to the redshifting of the PAH template, which is a more sensitive function of redshift than the continuum.

5.1. The Class I-II-III Classification and Evolutionary Scheme for SMGs

The total integrated infrared luminosity and the hard X-ray luminosity are essentially global properties of these simulations. Hence, we investigate where SMGs from our merger simulations would lie on a \(L_{IR} - L_X\) plane. Figure 18 marks in red the location of SMGs (i.e., \(F_{850,\mu m} > 1\) mJy for simulations placed at \(z = 2\), at a luminosity distance of 15.5 Gpc) on the \(L_{IR} - L_X\) plane, with divisions into class I, class II, and class III, which correspond to

---

**Fig. 13.**—Rest-frame emergent SED during the quasar from the h320 simulation, shown here over 200 viewing angles, compared to data of a SMG at \(z = 2.578\) (denoted GN04 in Pope et al. 2006). [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 14.**—Comparison to SHARC-2 and SCUBA data reported in Kovacs et al. (2006). The dash–double-dotted line is the h160 simulation, the solid line is e226, the dashed line is e320, and the dash-dotted line is e500; all are shown close to the peak of their submillimeter bright phase.

**Fig. 15.**—Observed \(F_{850,\mu m}\) flux (mJy) as a function of the ratio of black hole luminosity to total luminosity.

**Fig. 16.**—Observed \(F_{850,\mu m}\) flux (mJy) as a function of the X-ray luminosity.
$L_{IR} \approx 70L_X$ (the best-fit line that goes through our simulated data), $L_{IR} \approx 25L_X$ (the traditional quasar line; e.g., Elvis et al. 1994), and $L_{IR} \approx 5L_X$, respectively. Most of the SMGs studied by Alexander et al. (2005a) were found to have $L_{IR} \sim 200L_X$, on the basis of the radio far-IR correlation. Indeed, quite a few from our simulations have similar $L_{IR}/L_X$ values, although most have lower values. Interestingly, samples of quasars (e.g., Page et al. 2001) have similar $F_{850\mu m}$ values as SCUBA selected galaxies, which suggests that SMGs as defined by their 850 $\mu m$ fluxes are a diverse and broad class of objects, as already highlighted by observational studies on the basis of their radio and optical properties (Ivison et al. 2000).

Figure 18 demonstrates the diversity of SMGs, which traverse the class I–class II divide; some SMGs would fall on the traditional quasar line ($L_{IR} \gtrsim 25L_X$), yet many have higher values of $L_{IR}/L_X$. This shows explicitly that SMGs are a broader class of systems than quasars or starbursts, as selecting on the basis of the radio far-IR correlation. Indeed, quite a few of the systems in our simulations, which suggests that the formation of such objects at $z \sim 2$ may be described by major mergers, whose time evolution is influenced by feedback from the central AGN. As mentioned previously, the current merger simulations do not resolve the inner few parsecs, which may well be Compton thick and attenuate even the hard X-rays. However, Figure 18 does show that quasars like 3C 273 in elliptical (McLeod & Rieke 1994) host galaxies (although see recent work by Martel et al. [2003] which identifies intricate features in the host galaxy not captured in early $HST$ images), which are presumably more evolved, do lie closer to the class III region than Mrk 463 or UGC 5101, which are interpreted to be in an earlier stage of a merger (Sanders & Mirabel 1996).

A natural question to ask at this point is whether this classification scheme may be interpreted also as an evolutionary scheme within the context of the merger simulations studied here. Figure 19 shows the time evolution of the rest-frame continuum SED for the h320 simulation during the class I, class II, and class III phases. As the simulation progresses and obscuring columns of dust and gas are reduced due to continued star formation and feedback, more of the energy is distributed to shorter wavelengths, in a fashion similar to the time evolution of the SEDs for local ULIRGs as discussed by Chakrabarti et al. (2007).

Figure 20 presents the time evolution of the star formation rate, with the three classes marked, along with the time evolution of the 3.6 $\mu m$ image, and shows the track that a particular simulation

---

**Fig. 17.**—IRAC color-color plot in observed frame, with all simulations placed at $z = 0.3$ (left), $z = 1$ (middle), $z = 2$ (right). Crosses designate the continuum and squares the combined spectrum, i.e., the continuum and the PAH model, as before. Note the slightly “bunny-ear” shape of the IRAC color-color plot for the $z = 0.3$ slice.

---

**Fig. 18.**—Class I, class II, class III designation scheme for SMGs. $L_{IR} \gtrsim 70L_X$ is class I, $L_{IR} \gtrsim 25L_X$ is class II, $L_{IR} \lesssim 5L_X$ is class III. Points shown in red are those that have $F_{850\mu m} \gtrsim 1$ mJy at $z = 2$, i.e., would be empirically designated as SMGs. Yellow asterisks show observed sources from the literature.

---

**Fig. 19.**—Time evolution of the continuum rest-frame SED for h320, class I–class II–class III. As the obscuring columns of dust are lowered, more of the emitted energy shifts from the longer wavelengths to the shorter wavelengths.

[See the electronic edition of the Journal for a color version of this figure.]
(h320) would follow on the $L_{\text{IR}}$-$L_X$ diagram (marked in yellow in the bottom panel of the $L_{\text{IR}}$/$L_X$ diagram). As shown, the system starts out at high values of $L_{\text{IR}}$/$L_X \sim 100$, and then after reaching a peak in $L_X$, progressively moves down in $L_{\text{IR}}$/$L_X$ toward the bottom portion of this diagram, which we have marked as class III, and which we associate with elliptical merger remnants. (Other simulations evolve in a generally similar manner.) The $L_{\text{IR}}$/$L_X$ values for ellipticals are not well determined, unfortunately. Extrapolating from SCUBA observations of a sample of elliptical galaxies (Di Matteo et al. 1999), we suggest that $L_{\text{IR}}/L_X \sim 5$ may represent an upper bound for ellipticals. We emphasize that the class III designation is highly uncertain owing to the lack of a determination for $L_{\text{IR}}$ for merger remnants (although see Temi et al. 2005 for a discussion of a correlation between the mid-IR emission and age of ellipticals), as well as the wide range in X-ray luminosities (Mathews et al. 2006; O’Sullivan et al. 2001, 2004; Allen et al. 2000; Fabbiano 1989) and complex range of phenomena that produce X-ray luminosities in ellipticals, i.e., X-ray emission from hot gas, black hole, or residual star formation. Nonetheless, the increase in $L_X/L_B$ with age (Mackie & Fabbiano 1997; O’Sullivan et al. 2001) does suggest that the amount of X-ray–emitting hot gas increases with time relative to the amount of cold (infrared-emitting) gas. It will also be useful to directly compare correlations between photometric and kinematic correlations for merger remnants, as explored recently by Rothberg & Joseph (2006) to better quantify this tentative evolutionary scheme. We study correlations between kinematic and multiwavelength photometric properties in a future paper, and analyze a larger set of simulations to quantitatively address the transition from SMGs to ellipticals. From our preliminary analysis here, Figure 20 does suggest that the evolution of SMGs may be qualitatively understood in a relatively simple manner, wherein the system occupies some characteristic region of the $L_{\text{IR}}$-$L_X$ diagram during each phase of its lifetime.

6. CONCLUSION

1. Our simulations of gas-rich major mergers with black hole feedback naturally lead to the production of SMGs, which match photometric observations. The SMGs formed in these simulations have star formation rates of $\sim 500-1000 M_\odot$ yr$^{-1}$, infrared luminosities of $\sim 1-5 \times 10^{12} L_\odot$, and virial velocities of $\sim 300-400$ km s$^{-1}$.

2. We comment on the $M_{\text{BH}}$-$M_*$ relation for SMGs, and its inference from observations. We do find that the black holes in SMGs are in a rapidly growing phase, and grow by factors of $\sim 5$ between $z \sim 2$ and the present day (assuming Eddington-limited accretion in deriving black hole masses would lead to SMGs falling 2 orders of magnitude below the local relation).

3. We demonstrate that clustering in IRAC color-color space can be naturally explained within the context of the merger simulations studied here; clustering in this context translates to the system spending more of its lifetime in a given region of color-color space, and it is also positively correlated with the stars dominating in their contribution to the bolometric luminosity. We recover a similar percentage of sources occupying the AGN-demarcated region as in the Lacy et al. (2004) plot. We find that use of a PAH template produces a simulated IRAC color-color plot that is similar to the observed $z = 0.3$ IRAC color-color plot.

4. We predict a correlation between the rest-frame infrared, 70 $\mu$m, and 24 $\mu$m luminosity and the hard X-ray luminosity for SMGs, with an increase in scatter at low X-ray luminosities. To aid observational studies, we quantify the far-infrared X-ray
correlations. These predictions will be directly testable by future instruments, such as Herschel, and possibly through source stacking analysis using current Spitzer data.

5. Our photo albums of the lifetimes of SMGs visually illustrate the differential variation in surface brightness between the SCUBA and IRAC bands. Of particular note is the increase in apparent brightness in the IRAC bands, which is concomitant with a decrease in brightness in the SCUBA bands, toward the late phases of the merger. This is due to more of the emitted energy shifting to the shorter wavelengths as continued feedback and star formation lower the amount of obscuring material. We also demonstrate that the morphology as seen in these bands is partly a function of orbital inclination, with coplanar mergers producing disklike morphologies in the active phase. As such, even galaxies with observed disklike morphologies may have experienced major (coplanar) mergers. The simulations generally have emission extending to ~10 kpc in the active phase in the IRAC and SCUBA bands.

6. We find that our predicted SEDs are in good agreement with recent multiwavelength photometry. We show the IRAC color-color plot for galaxies in a narrow redshift slice, with $z \sim 2$, which results in a flattened elliptical distribution of colors unlike the nearly spherical distribution at low redshifts.

7. We depict the variation of the observed 850 $\mu$m flux as a function of both the X-ray luminosity and the ratio of the black hole luminosity to the total bolometric luminosity. There is a general trend for SMGs on the bright end at $z \sim 2$ to have a significant ($\geq 50\%$) contribution from the black hole to their total bolometric luminosity.

8. The correlations and photometric properties of SMGs listed here are predictions of this model and can be observationally tested by obtaining a large sample ($\sim 100$) of observations in a narrow redshift range.

9. We find that SMGs are a broader class of systems than quasars or starbursts. We introduce a simple, heuristic classification scheme for SMGs on the basis of their $L_{IR}/L_{X}$ ratios, $L_{IR} \gtrsim 70L_{X}$ is class I, $L_{IR} \gtrsim 25L_{X}$ is class II, $L_{IR} \lesssim 5L_{X}$ is class III. We suggest that this may also be interpreted as an evolutionary scheme as SMGs transit from a X-ray underluminous infrared bright stage through the quasar phase to merger remnants.

We thank George Rybicki for helpful discussions on scattering processes. We thank Giovanni Fazio, Pauline Barmby, and Tiziana Di Matteo for helpful discussions. We especially thank Jiasheng Huang for many helpful discussions on the observations of (and interpretations of) SMGs. We also thank Volker Springel and Dusan Keres for constructive feedback on the simulations discussed in this paper. S. C. is supported by an NSF Postdoctoral Fellowship. The simulations were performed on the Institute for Theory and Computation Cluster.

APPENDIX A

DUST OPACITY ASSUMPTIONS

To calculate the dust thermal emission from these simulations, we assume that the dust follows the gas distribution, which is composed of a cold and diffuse phase, as described in SH03. Dust grain formation and evolution (i.e., destruction due to shocks, or radiation pressure on dust grains) is therefore not treated here. These processes have been treated approximately in the context of protostars using 2D radiation hydrodynamical simulations (Yorke & Sonnhalter 2002). The large dynamic range needed to treat galaxies in a three-dimensional context and accompanying physical complexity (multiphase ISM, star formation, feedback processes) currently render this a difficult problem that has yet to be addressed. Our approach here is to make empirically motivated assumptions about the dust opacity, and choose a fiducial value for presentation of results in the paper.

Figure 21 (left) depicts the inclination averaged SED from the quasar phase of the e320 simulation, for three different choices of the dust-to-gas ratio in the diffuse phase, relative to the Milky Way value. The dust-to-gas ratio in the cold phase is set to 1/100. A comparable dust-to-gas ratio in the diffuse phase is therefore not treated here. These processes have been treated approximately in the context of protostars using 2D radiation hydrodynamical simulations (Yorke & Sonnhalter 2002). The large dynamic range needed to treat galaxies in a three-dimensional context and accompanying physical complexity (multiphase ISM, star formation, feedback processes) currently render this a difficult problem that has yet to be addressed. Our approach here is to make empirically motivated assumptions about the dust opacity, and choose a fiducial value for presentation of results in the paper. The process of grain formation and destruction, as well as its effect on the dynamics, to be incorporated in the hydrodynamic simulation. The middle and right panels of Figure 21 demonstrate that the morphology as seen in these bands is partly a function of orbital inclination, with coplanar mergers producing disklike morphologies in the active phase. As such, even galaxies with observed disklike morphologies may have experienced major (coplanar) mergers. The simulations generally have emission extending to ~10 kpc in the active phase in the IRAC and SCUBA bands.

8. The correlations and photometric properties of SMGs listed here are predictions of this model and can be observationally tested by obtaining a large sample ($\sim 100$) of observations in a narrow redshift range.

9. We find that SMGs are a broader class of systems than quasars or starbursts. We introduce a simple, heuristic classification scheme for SMGs on the basis of their $L_{IR}/L_{X}$ ratios, $L_{IR} \gtrsim 70L_{X}$ is class I, $L_{IR} \gtrsim 25L_{X}$ is class II, $L_{IR} \lesssim 5L_{X}$ is class III. We suggest that this may also be interpreted as an evolutionary scheme as SMGs transit from a X-ray underluminous infrared bright stage through the quasar phase to merger remnants.

We thank George Rybicki for helpful discussions on scattering processes. We thank Giovanni Fazio, Pauline Barmby, and Tiziana Di Matteo for helpful discussions. We especially thank Jiasheng Huang for many helpful discussions on the observations of (and interpretations of) SMGs. We also thank Volker Springel and Dusan Keres for constructive feedback on the simulations discussed in this paper. S. C. is supported by an NSF Postdoctoral Fellowship. The simulations were performed on the Institute for Theory and Computation Cluster.

APPENDIX A

DUST OPACITY ASSUMPTIONS

To calculate the dust thermal emission from these simulations, we assume that the dust follows the gas distribution, which is composed of a cold and diffuse phase, as described in SH03. Dust grain formation and evolution (i.e., destruction due to shocks, or radiation pressure on dust grains) is therefore not treated here. These processes have been treated approximately in the context of protostars using 2D radiation hydrodynamical simulations (Yorke & Sonnhalter 2002). The large dynamic range needed to treat galaxies in a three-dimensional context and accompanying physical complexity (multiphase ISM, star formation, feedback processes) currently render this a difficult problem that has yet to be addressed. Our approach here is to make empirically motivated assumptions about the dust opacity, and choose a fiducial value for presentation of results in the paper. The process of grain formation and destruction, as well as its effect on the dynamics, to be incorporated in the hydrodynamic simulation. The middle and right panels of Figure 21 demonstrate that the morphology as seen in these bands is partly a function of orbital inclination, with coplanar mergers producing disklike morphologies in the active phase. As such, even galaxies with observed disklike morphologies may have experienced major (coplanar) mergers. The simulations generally have emission extending to ~10 kpc in the active phase in the IRAC and SCUBA bands.

8. The correlations and photometric properties of SMGs listed here are predictions of this model and can be observationally tested by obtaining a large sample ($\sim 100$) of observations in a narrow redshift range.

9. We find that SMGs are a broader class of systems than quasars or starbursts. We introduce a simple, heuristic classification scheme for SMGs on the basis of their $L_{IR}/L_{X}$ ratios, $L_{IR} \gtrsim 70L_{X}$ is class I, $L_{IR} \gtrsim 25L_{X}$ is class II, $L_{IR} \lesssim 5L_{X}$ is class III. We suggest that this may also be interpreted as an evolutionary scheme as SMGs transit from a X-ray underluminous infrared bright stage through the quasar phase to merger remnants.

We thank George Rybicki for helpful discussions on scattering processes. We thank Giovanni Fazio, Pauline Barmby, and Tiziana Di Matteo for helpful discussions. We especially thank Jiasheng Huang for many helpful discussions on the observations of (and interpretations of) SMGs. We also thank Volker Springel and Dusan Keres for constructive feedback on the simulations discussed in this paper. S. C. is supported by an NSF Postdoctoral Fellowship. The simulations were performed on the Institute for Theory and Computation Cluster.
depict the variation in SEDs prior to the quasar phase and during the quasar phase, respectively, for the h320 simulation. Both 1/10th and comparable dust-to-gas ratios in the diffuse and dense phases yield reasonable results during the starburst phase for the h320 simulation. Since we focus on the SMG phase in this paper, with the intent of delineating the starburst and quasar phases, we make the simplifying assumption that the diffuse phase dust-to-gas ratio is 1/10th of the cold phase during the course of the simulation.

We now demonstrate that the infrared emission from the obscuring dust envelope surrounding young star clusters does not significantly contribute to the emergent SED of ULIRGs or SMGs. In such systems, the sources of luminosity are very compactly distributed due to a large amount of gas (and dust) having been funneled into the central few parsecs as a result of the major merger. Dopita et al. (2005) calculated the emergent SEDs of galaxies including the effect of a time-dependent dispersal of the natal dust envelope around young star clusters using the one-dimensional MAPPINGs code which calculates the dust temperature locally, and found good agreement with observations. The SPH simulations do not include the obscuration around young star clusters, so our calculations reported in the paper have not treated this effect. Here, we use a simple ad hoc prescription to see if this effect makes a significant difference to the emergent SEDs of SMGs. We assume that young star clusters \( t_{age} < 1 \) Myr; to make this point more clear, we also include a case with \( t_{age} < 10 \) Myr) are surrounded by a natal dust envelope of surface density \( \Sigma = 1 \) g cm\(^{-2}\) and have a light-to-mass ratio of \( L/M = 20 \hbox{\,L}_\odot \, M_\odot^{-1}\), which are typical of young star clusters or star-forming clumps (Plume et al. 1997; Gilbert & Graham 2001; de Marchi et al. 1997). For these young star clusters, we replace the input stellar spectral template with the emergent infrared SED given by the Chakrabarti & McKee (2005) formalism for a dust envelope of \( L/M = 20 \hbox{\,L}_\odot \, M_\odot^{-1}\) and \( \Sigma = 1 \) g cm\(^{-2}\). This result is shown in Figure 22 (medium gray line) and compared to our standard case (black line). The lack of difference in emergent SEDs should be expected, as the compact starburst is highly obscured such that the attenuation between star clusters (due to the cold clouds and the diffuse gas) in the inner nuclear regions is very large, reaching average values of \( A_v \sim 100 \) or greater.

To further demonstrate that this effect will not alter the emergent SEDs of SMGs, we also consider a more extreme case; we include the infrared emission from star clusters with ages less than 10 Myr, with the same parameters as above. This case (shown by the light gray line in Fig. 22) is also not significantly different from our standard case, even though star particles with ages less than 10 Myr contribute about 19% to the total luminosity (this is during the quasar phase where the black hole provides about 70% of the luminosity). We have also checked that our results are not affected by slight variations in our choice of these parameters, i.e., varying by a factor of \( \sim 2 \) the \( L/M \) and \( \Sigma \) relative to our adopted values here. This effect may be relevant in more translucent galaxies where the obscuration between star clusters is not as large as in the extreme environments of SMGs. In principle, a time-dependent dispersal of the natal dust envelopes surrounding young star clusters, as studied by Dopita et al. (2005), as well as the three-dimensional nature of the dust envelopes of young star clusters would provide a more realistic description of this effect. However, it is clear from our calculations that this effect can be neglected in the extreme environments of ULIRGs and SMGs, even when young star clusters provide a sizable fraction of the luminosity.

**APPENDIX B**

**850 \( \mu \)m FLUX OF SIMULATIONS**

Figure 23 shows the observed 850 \( \mu \)m flux as a function of time for galaxies with varying orbital inclination for e226, h226, e320, and h320. While there is no clear difference between the peak fluxes of the galaxies shown here of varying orbital inclination, the coplanar mergers (shown here as the solid lines) do have a sharper decline in their 850 \( \mu \)m flux as a function of time. Finally, Figure 24 contrasts the time evolution of the 850 \( \mu \)m flux when the WD01 opacity (solid line) is used instead of the WD01 model with inclusion of ice mantles (dotted line). Since the observed 850 \( \mu \)m flux is nearly optically thin, the effect of adding ice mantles corresponds to increasing the 850 \( \mu \)m flux. Figure 25 shows the e226 and e320 simulations with the Salpeter (solid line) and Kroupa (dashed line) IMFs. Using the Kroupa IMF leads to a slight increase in the observed 850 \( \mu \)m flux (by about \( \sim 30\%\)).

Figure 26 shows the time evolution of the observed 850 \( \mu \)m fluxes for the e160 and h160 simulations, which are designed to have virial velocities representative of local ULIRGs (the e160 simulation has 40% gas fraction initially, while the h160 simulation has
Fig. 23.—$F_{850 \mu m}$ (in observed frame for galaxies at $z = 2, D_L = 15.5$ Gpc for $H_0 = 70, \Omega_M = 0.3, \Omega_\Lambda = 0.7$) vs. time for the SMGs of varying orbital inclination for h226, e226, h320, and e320. The solid line shows the coplanar cases: h226 and h320, and the dotted line the non-coplanar cases e226 and e320.

Fig. 24.—$F_{850 \mu m}$ (in observed frame for galaxies at $z = 2, D_L = 15.5$ Gpc) vs. time for the SMGs of varying dust opacity shown here for e226, with and without the inclusion of ice mantles. Solid line has the WD01 opacity, while the dotted line includes ice mantles.

Fig. 25.—$F_{850 \mu m}$ (in observed frame for galaxies at $z = 2, D_L = 15.5$ Gpc) vs. time for e226 and e320, shown here for Salpeter (solid line) and Kroupa (dashed line) IMFs.
100% at the start of the simulation). These simulations have submillimeter fluxes similar to those of local LIRGs and ULIRGs. Averaging the 850 μm fluxes in Table 3 of Dunne & Eales (2001) gives 183 mJy, with Arp 220 topping the list at 832 mJy. Such objects at $D_L = 77$ Mpc would be bright in the submillimeter for a longer fraction of their lifetime than at $z = 2$, as has been shown previously in this section. Although we do not derive the submillimeter luminosity functions in this paper, it is clear that simulations of gas-rich major mergers naturally lead to the production of SMGs.

REFERENCES

Alexander, D. M., et al. 2005a, ApJ, 632, 736
———. 2005b, Nature, 442, 738
Allamandola, L. J., et al. 1992, ApJ, 399, 134
Allen, S. W., Di Matteo, T., & Fabian, A. C. 2000, MNRAS, 311, 493
Alonso-Herrero, A., et al. 2004, ApJS, 154, 155
Armus, L., et al. 2007, ApJ, 656, 148
Barnes, J. E., & Hernquist, L. E. 1991, ApJ, 370, L65
———. 1996, ApJ, 471, 115
Baugh, C. M., et al. 2005, MNRAS, 356, 1191
Bautz, M. W., et al. 2000, ApJ, 543, L119
Bjorkman, J. E., & Wood, K. 2001, ApJ, 554, 615
Blain, A. W., et al. 2002, Phys. Rep., 369, 111
———. 2004a, ApJ, 611, 52
———. 2004b, ApJ, 611, 725
Borys, C., et al. 2005, ApJ, 635, 853
Bouche, N., et al. 2007, ApJ, 658, 840 (C07)
Chapman, S. C., et al. 2003a, ApJ, 599, 92
———. 2003b, Nature, 422, 695
———. 2004, ApJ, 611, 732
———. 2005, ApJ, 622, 772
Comastri, A., et al. 1995, A&A, 296, 1
Cox, T. J., et al. 2006a, ApJ, 643, 692
———. 2006b, ApJ, 650, 791
———. 2008, ApJ, submitted
Croom, S. M., et al. 2005, MNRAS, 356, 415
Dale, D. A., & Helou, G. 2002, ApJ, 576, 159
Dasyra, K. M, et al. 2006, ApJ, 638, 745
De Grijp, M. H. K., et al. 1985, Nature, 314, 240
de Marchi, G., et al. 1997, ApJ, 479, L27
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Di Matteo, T., et al. 1999, MNRAS, 305, 492
Dopita, M. A., et al. 2005, ApJ, 619, 755
Draine, B. T., & McKee, C. F. 1993, ARA&A, 31, 373
Dunne, L., & Eales, S. A. 2001, MNRAS, 327, 697
Dunne, L., et al. 2000, MNRAS, 315, 115
Efstathiou, A., & Rowan-Robinson, M. 2003, MNRAS, 343, 322
Elvis, M., et al. 1994, ApJS, 95, 1
Fabbiano, G. 1989, ARA&A, 27, 87
Farrah, D., et al. 2002, MNRAS, 335, 1163
George, I. M., et al. 1998, ApJS, 114, 73
Genzel, R., et al. 2003, ApJ, 584, 633
———. 2006, Nature, 442, 786
Gilbert, A., & Graham, J. R. 2001, in Starburst Galaxies: Near and Far, ed. L. Tacconi & D. Lutz (Heidelberg: Springer), 123
Gilfanov, M., et al. 2004, MNRAS, 347, L57
Goldader, J. D., et al. 2002, ApJ, 568, 651
Greve, T. R., Ivison, R. J., & Papadopoulos, P. P. 2004, A&A, 419, 99
Hopkins, P., Richards, G., & Hernquist, L. 2007, ApJ, 654, 731 (HRH07)
Horns, P., et al. 2005, ApJ, 630, 716
Hughes, D. H., et al. 1997, MNRAS, 289, 766
Iono, D., et al. 2006, ApJ, 640, L1
Ivezic, Z., & Elitzur, M. 1997, MNRAS, 287, 799
Ivison, R. J., et al. 1998, MNRAS, 298, 583
———. 2000, MNRAS, 315, 209
Kennicutt, R. C., Jr. 1998, ApJ, 498, 541
Klaas, U., et al. 2001, ApJ, 379, 823
Kovaš, A., et al. 2006, ApJ, 650, 592
Krumholz, M., & McKee, C. F. M. 2005, ApJ, 630, 250
Lacy, M., et al. 2004, ApJS, 154, 166
Leitherer, C., et al. 1999, ApJS, 123, 3
Li, Y., et al. 2008, ApJ, 678, 41
Lilly, S. 1999, in ASP Conf. Ser. 193, The Hy-Redshift Universe, ed. A. J. Bunker & W. J. M. van Breugel (San Francisco: ASP), 191
Lucy, L. B. 1999, A&A, 344, 282
Mackie, G., & Fabbiano, G. 1997, in ASP Conf. Ser. 116, The Nature of Elliptical Galaxies, ed. M. Arnaboldi, G. S. Da Costa, & P. Saha (San Francisco: ASP), 401
Magdziarz, P., & Zdziarski, A. A. 1995, MNRAS, 273, 837
Magorrian, J., et al. 1998, AJ, 115, 2285
Marconi, A., et al. 2004, MNRAS, 351, 169
Martiń, A. R., et al. 2003, AJ, 125, 2964
Mathews, W. G., et al. 2006, ApJ, 652, L17
McLeod, K. K., & Rieke, G. H. 1994, ApJ, 431, 137
Mihos, C. J., & Hernquist, L. 1994, ApJ, 431, L9
———. 1996, ApJ, 464, 641
Pope, A., et al. 2006, MNRAS, 370, 1185
Pope, A., et al. 2006, ApJ, 597, L113
Nesvadba, N., et al. 2007, A&A, 475, 145
O’Sullivan, E., Forbes, D. A., & Ponnam, T. J. 2001, MNRAS, 324, 420
O’Sullivan, E., & Ponnam, T. J. 2004, MNRAS, 349, 535
Page, M. J., et al. 2001, Science, 294, 2516
Perola, G. C., et al. 2002, A&A, 389, 802
Plume, R., et al. 1997, ApJ, 476, 730
Pollack, J. B., et al. 1994, ApJ, 421, 615
Pope, A., et al. 2006, MNRAS, 370, 1185
Rigby, J. R., et al. 2004, ApJS, 154, 160
Rothberg, B., & Joseph, R. D. 2006, AJ, 132, 976
Rowan-Robinson, M. 2000, MNRAS, 316, 885
Sadler, E. M., et al. 2002, MNRAS, 329, 227
Sajina, A., Lacy, M., & Scott, D. 2005, ApJ, 621, 256
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Scoville, N. Z., et al. 2000, AJ, 119, 991
Shu, F. H., et al., 2007, ApJ, 662, L75
Silva, L., et al. 1998, ApJ, 509, 103
Smail, I., Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, L5
Smith, J. D. T., et al. 2007, ApJ, 656, 770
Soifer, B. T., et al. 1984, ApJ, 278, L71
———. 1987, ApJ, 320, 238
———. 2000, AJ, 119, 509
Spoon, H. W. W., et al. 2002, A&A, 385, 1022
Springel, V. 2005, MNRAS, 364, 1105
Springel, V., di Matteo, T., & Hernquist, L. 2005a, MNRAS, 361, 776
———. 2005b, ApJ, 620, L79
Springel, V., & Hernquist, L. 2003, MNRAS, 339, 289 (SH03)
Swinbank, A. M., et al. 2004, ApJ, 617, 64
Tacconi, L. J., et al. 2006, ApJ, 640, 228
———. 2008, ApJ, 680, 246
Telfer, R. C., et al. 2002, ApJ, 565, 773
Temi, P., et al. 2005, ApJ, 635, L25
Ueda, Y., et al. 2003, ApJ, 598, 886
Vazquez, G. A., & Leitherer, C. 2005, ApJ, 621, 695
Vignali, C., Brandt, W. N., & Schneider, D. P. 2003, AJ, 125, 433
Weingartner, J., & Draine, B. T. 2001, ApJ, 548, 296 (WD01)
Whitney, B. A., et al. 2003, ApJ, 598, 1079
Wolf, S., 2003, ApJ, 582, 859
Yan, L., et al. 2005, ApJ, 628, 604
———. 2007, ApJ, 658, 778
Yorke, H., & Sonnhalter, C. 2002, ApJ, 569, 846