SIMULATIONS OF DUST IN INTERACTING GALAXIES. I. DUST ATTENUATION

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ABSTRACT

A new Monte Carlo radiative transfer code, SUNRISE, is used in conjunction with hydrodynamic simulations of major galaxy mergers to calculate the effects of dust in such systems. Dust has a profound effect on the emerging radiation, consistent with observations of dust absorption in starburst galaxies. The dust attenuation increases with luminosity such that at peak luminosities ~90% of the bolometric luminosity is absorbed by dust. We find that our predictions agree with observed relationships between the UV spectral slope and the fraction of light absorbed by dust (IRX-β) and observational estimates of the optical depth as a function of intrinsic B-band or UV luminosity. In general, the detailed appearance of the merging event depends on the stage of the merger and the geometry of the encounter. The fraction of bolometric energy absorbed by the dust, however, is a robust quantity that can be predicted from the intrinsic properties bolometric luminosity, baryonic mass, star formation rate, and metallicity of the simulated system. This paper presents fitting formulae, valid over a wide range of masses and metallicities, from which the absorbed fraction of luminosity (and consequently also the infrared dust luminosity) can be predicted. The attenuation of the luminosity at specific wavelengths can also be predicted, albeit with a larger scatter due to the variation with viewing angle. These formulae for dust attenuation are consistent with earlier studies and would be suitable for inclusion in theoretical models, e.g., semianalytic models, of galaxy formation and evolution.

Subject headings: dust, extinction — galaxies: interactions — galaxies: starburst — methods: numerical — radiative transfer

Online material: color figures

1. INTRODUCTION

Galaxy mergers produce some of the most spectacular events in the universe. Locally, they are responsible for the most luminous galaxies, ultraluminous infrared galaxies (ULIRGs; Sanders & Mirabel 1996). At higher redshifts they may be responsible for the sources seen in the submillimeter (Smail et al. 1997), and they may even be a dominant mode of star formation in the early universe (Somerville et al. 2001; Elbaz & Cesarsky 2003; Bell et al. 2005). Because the most luminous objects are also generally the most dust-obscured, it was not until the launch of IRAS that the existence of ULIRGs was discovered. What in the optical appeared to be fairly unimpressive, albeit peculiar, galaxies turned out to be the brightest infrared sources in the local universe. It is now clear that starbursts and dust generally go hand in hand. The large amounts of gas necessary to fuel a major starburst bring with them large column densities of dust, obscuring the starburst and reradiating the energy in the far-infrared. In addition, rapid star formation quickly enriches the region with metals, further increasing the amount of dust. Including the effects of dust is thus crucial when studying these systems.

Theoretical studies of dust attenuation in galaxies have used various approaches. One is to fit observations of spectral energy distributions (SEDs) of individual galaxies. Kylafis & Bahcall (1987) pioneered this method, studying the edge-on galaxy NGC 891. Xilouris et al. (1999) fit optical isophotes of seven nearly edge-on spiral galaxies using a model with a stellar disk and bulge and a dust disk. They concluded that these spiral galaxies had central face-on optical depth less than 1 in all optical bands and that the dust disk had a scale height roughly half that of the stars, but a scale length about 1.4 times larger than the stars. Numerous authors have found that in addition to a stellar disk and bulge and a dust disk, it is necessary to introduce a highly extinguished population of young stars in order to obtain a high enough level of far-infrared luminosity. This has been modeled either as additional absorption of light from young stars by their parent molecular clouds (Silva et al. 1998; Charlot & Fall 2000; Popescu et al. 2000) or as an additional, thin, dust disk (Popescu et al. 2000). These studies show that it is possible to fit observations of dust in galaxies with reasonably simple models.

Another approach is to study the behavior of dust attenuation in analytic models, surveying a large parameter space. This is useful for gaining an intuitive understanding of the effects of dust. Witt et al. (1992) studied the radiation emerging from star-forming regions with various spherical distributions of stars and dust, emphasizing the sensitivity with which the effects of dust depend on the relative geometry of stars and dust and the fact that scattering partially compensates reddening by dust. Witt & Gordon (1996, 2000) extended this model to include small-scale clumping

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of the dust, finding that the effective optical depth of a clumpy distribution of dust is always smaller than the equivalent homogenous distribution and that clumping also reduces the reddening and apparent albedo of the dust. Városi & Dwek (1999) calculated analytical approximations for systems with a similar geometry. Bianchi et al. (1996) studied extinction and polarization properties of dusty spiral galaxies and also found that scattering reduced both attenuation and reddening. They also emphasized the dramatic effect that the geometric distribution of dust and stars have on the attenuation and reddening properties. Their study was extended by Ferrara et al. (1999), who studied dust attenuation in a large number of disk plus bulge models with a varying bulge-to-disk ratio and relative distributions of stars and dust, tabulating attenuation curves and the dependence of dust attenuation on inclination. They found that models that were optically thick in V band and that had a dust scale height larger than that of the stars fit the inclination dependence better, in conflict with the findings of Xilouris et al. (1999). Bianchi et al. (2000) extended the model of Ferrara et al. (1999) to include a clumpy interstellar medium (ISM). They noted that while models with clumpy dust but homogenous stellar distributions are less opaque than their homogenous equivalents, models that have clumpy stellar as well as dust distributions can have a larger fraction of the starlight absorbed by the dust, depending on what fraction of the stellar light is emitted from within the clumps. Pierini et al. (2004) also studied a range of bulge-plus-disk models. They emphasized that the effects of dust on the light from the bulge are qualitatively different from the effects on the disk and that the contribution of scattered radiation is important, particularly in the UV. Tufts et al. (2004) applied the model of Popescu et al. (2000) with a wide range of parameters, also studying the differing effects of dust on the disk and the bulge. They also noted that the effect of increasing the bulge-to-disk ratio can be largely degenerate with the effect of increasing opacity in a bulgeless disk. In general, the obvious conclusion from the studies is that the effects of dust on the radiation emerging from galaxies are highly nontrivial and are sensitive to the detailed geometric distributions of the different components.

The third approach, used in this study, is to derive the geometry of stars and dust from hydrodynamic simulations. By using hydrodynamic simulations, the geometry of stars and dust can be linked to the dynamical evolution of the galaxy and its star formation history. This becomes especially important when studying dynamically disturbed systems such as merging galaxies, whose geometries cannot be well described by disk-plus-bulge models.

Several previous efforts at simulating merging galaxies using hydrodynamic N-body codes with star formation and supernova feedback have been presented in the literature (e.g., Mihos & Hernquist 1994, 1996; Springel 2000), recently also including feedback from black hole accretion (Springel et al. 2005b), but these efforts did not consider realistic observations of their simulations including the effects of dust. Bekki & Shioya (2000a, 2000b, 2001) did use a simple model for dust attenuation and reradiation along with N-body simulations to investigate major mergers. However, their modeling, using the “sticky particle” method (Schwarz 1981) and with no supernova feedback, did not allow them to capture essential features of the hydrodynamics of merging galaxies. This work builds on these earlier works, using a full radiative transfer model to study the effects of dust in a comprehensive suite of major-merger simulations.

Because of the complexity of this problem, both the hydrodynamic simulations and the treatment of dust carry numerous uncertainties. In order to ascertain whether our simulations are reproducing the effects of dust in real galaxies in a reasonable manner, we could ask several questions, reflecting various kinds of observational studies:

1. Do our simulations produce the correct amount of reddening for a given amount of attenuation?
2. Do our simulations produce the correct amount of attenuation as a function of the intrinsic galaxy properties (e.g., unextinguished luminosity, mass, etc.).
3. Do our simulations produce the correct dependence of attenuation on viewing angle?
4. In our simulations, how is the general morphological appearance of the galaxies modified by the presence of dust?

We compare the predictions of our simulations with observational results to address questions 1 and 2. We do not address question 3 at this time, as it applies mainly to undisturbed disk galaxies, while this paper concerns mergers. We also defer question 4 to later works, in which the appearance of the simulations will be studied in detail and compared with observed galaxies (P. Jonsson et al. 2005, in preparation and J. Lotz et al. 2005, in preparation) using new nonparametric measures of morphology (Lotz et al. 2004).

Having established at least qualitative agreement between our predictions and observations of dust attenuation and reddening in real galaxies, we emphasize one rather surprising result of our calculations: the presence of a tight correlation between the fraction of energy absorbed by dust and intrinsic quantities such as the luminosity, metallicity, and mass of the simulated systems. We provide simple fitting functions quantifying these relations, which can be used to estimate the absorption by dust in cosmological models of galaxy formation (such as semianalytic models).

2. MODEL DESCRIPTION

2.1. Model Galaxies

Several different, observationally motivated, dynamically self-consistent disk-galaxy models (listed in Table 1) are used in this study. The N-body realizations were generated in a manner similar to that used by Hernquist (1993), Springel & White (1999), and Springel (2000), with the difference that our galaxies were more directly created to mimic observed galaxies.

The Sbc galaxy, chosen to mimic a gas-rich, local late-type spiral galaxy, was modeled using median properties for Sbc galaxies from Roberts & Haynes (1994). The constraints used were disk size, dynamical mass, and gas fraction. Stellar mass was derived from luminosities from Roberts & Haynes (1994) using mass-to-light ratios from de Jong (1996b). The relation between stellar and gaseous scale lengths was taken from Broeils & van Woerden (1994), and bulge information from de Jong (1996a).

The dark matter halo, with a Navarro-Frenk-White profile (Navarro et al. 1997), was constrained by the dynamical mass using an assumed concentration of 11 and an assumed spin parameter of 0.05. Lower and higher mass variants of the Sbc galaxy, called Sbc− and Sbc+, respectively, were modeled using the 25th and 75th percentiles of the distributions of properties.

Another set of galaxies, the “G series,” was based on mean relations from the Sloan Digital Sky Survey. The disk scale length as a function of stellar mass was based on Shen et al. (2003), and bulge properties were taken from de Jong (1996a). The gas content as a function of stellar mass was obtained from Bell et al. (2003), and the radial extent of the gas disk from Broeils & van Woerden (1994). The parameters of the dark matter halos of these galaxies were determined by requiring that the galaxies obey the baryonic Tully-Fisher relation from Bell & de Jong.
The Galaxy Models Used for the Merger Simulations

| Model     | \(M_{10}^{\text{gal}}\) (M\(_{\odot}\)) | \(M_{10}^{\text{d}}\) (M\(_{\odot}\)) | \(R_d\) (kpc) | \(Z_{\odot}/R_d\) | \(R_d/R_d\) | \(f_0\) | \(f_b\) | \(R_g\) (kpc) | \(V_{\text{circ}}\) (km s\(^{-1}\)) | \(Z\) (Z\(_{\odot}\)) | \(N_{\text{p}}\) (10\(^4\)) |
|-----------|----------------------------------|----------------------------------|----------------|----------------|----------------|--------|--------|----------------|-----------------|----------------|----------------|
| Sbc\(^+\) | \(9.28 \times 10^{10}\)          | \(1.56 \times 10^{11}\)         | 7.0            | 0.125          | 3.0            | 0.52   | 0.10   | 0.60            | 210             | 1.12            | 3               |
| Sbc\(^-\) | \(8.12 \times 10^{10}\)          | \(1.03 \times 10^{11}\)         | 5.5            | 0.125          | 3.0            | 0.52   | 0.10   | 0.45            | 195             | 1.00            | 3               |
| G3        | \(1.16 \times 10^{11}\)          | \(6.22 \times 10^{10}\)         | 2.8            | 0.125          | 3.0            | 0.20   | 0.14   | 0.37            | 192             | 1.00            | 5               |
| Sbc\(^-\) | \(3.60 \times 10^{10}\)          | \(4.98 \times 10^{10}\)         | 4.0            | 0.125          | 3.0            | 0.52   | 0.10   | 0.40            | 155             | 0.70            | 3               |
| G2        | \(5.10 \times 10^{11}\)          | \(1.98 \times 10^{10}\)         | 1.9            | 0.2            | 3.0            | 0.23   | 0.08   | 0.26            | 139             | 0.56            | 3               |
| G1        | \(2.00 \times 10^{10}\)          | \(7.00 \times 10^{9}\)          | 1.5            | 0.2            | 3.0            | 0.29   | 0.04   | 0.20            | 103             | 0.40            | 2               |
| G6        | \(5.10 \times 10^{11}\)          | \(1.60 \times 10^{10}\)         | 1.1            | 0.2            | 3.0            | 0.38   | 0.01   | 0.15            | 67              | 0.28            | 1               |

Notes.—For the Sbc galaxies, nine mergers with different orbital geometries were used. For the other galaxies, only a prograde-prograde encounter was used. Col. (2): virial mass; col. (3): baryonic mass; col. (4): stellar disk scale length; col. (5): ratio of stellar-disk scale height and scale length; col. (6): ratio of scale lengths of gas and stellar disks; col. (7): gas fraction (of baryonic mass); col. (8): bulge fraction (of baryonic mass); col. (9): bulge scale radius; col. (10): circular velocity; col. (11): metallicity (gas and stellar); col. (12): number of gas particles.

These galaxies have significantly less gas than the Sbc models and cover a much larger range in mass.

The scale height of the gas in the galaxies is not shown in Table 1, since the gas rapidly adjusts to a scale height set by hydrostatic equilibrium. In simulations of isolated Sbc galaxies, the gas scale height in the central regions is approximately 0.35 kpc. At larger radii, the disk flares.

The galaxies were assigned an average metallicity for their luminosity, based on Zaritsky et al. (1994). This metallicity was used for both the stellar SEDs and the initial gas metallicity. Radial metallicity gradients were not included, making the dust scale length equal to the gas scale length and significantly larger than the stellar scale length. In the future, metallicity gradients will be included, bringing the dust scale length into better agreement with the observations of edge-on galaxies by Xilouris et al. (1999), mentioned previously. A decreasing dust content in the outer parts of the galaxy would also bring down the overall attenuation in the galaxies, which is higher than in observations of nearby spiral galaxies (Popescu & Tuffs 2002). In our isolated Sbc galaxy, 46% of the stellar luminosity is absorbed by dust, compared to 10%–30% in observed Sbc galaxies.

The procedure used to construct an N-body model from these observational constraints is quite complicated, and it is described in detail in Appendix A of Cox (2004), where further data on the model galaxies also can be found.

2.2. Galaxy Merger Simulations

The galaxy merger simulations, performed with the “entropy-conserving” version of the GADGET smoothed particle hydrodynamics (SPH) code (Springel et al. 2001; Springel & Hernquist 2002; Springel 2005), consist of encounters of identical copies of the galaxies listed in Table 1. Because of the very large parameter space, the number of simulations needed to exhaustively sample all possible initial conditions would be prohibitively large (on the order of thousands). Instead, our strategy was to define a few reasonably realistic and representative cases based on information from observations and cosmological simulations.

There are three main differences from previous hydrodynamic simulations of galaxy mergers. First, our simulations include efficient supernova feedback, which pressurizes star-forming regions by depositing supernova feedback energy into a reservoir, which is only allowed to cool on a timescale much longer than the thermal cooling timescale. This reservoir is designed to phenomenologically mimic the effect of sources of pressures such as turbulence, magnetic fields, etc., which are not included in the simulations. The exploration of the effects of different feedback parameters on the properties of the merger is the subject of Cox et al. (2005); the parameter set used for the simulations analyzed here was n21w. Second, we adjusted the normalization of the star formation law (effectively the free parameter in the relationship between gas density and star formation rate density), so that our isolated galaxies initially lie on the observed “Kennicutt law” (Kennicutt 1998). The simulations presented in Springel (2000) were inadvertently normalized too low (V. Springel 2001, private communication). Third, we make use of an accurate treatment of hydrodynamics using the GADGET version described in Springel & Hernquist (2002), which correctly handles pointlike energy injections like those resulting from the supernova feedback scheme. These modifications contribute to the suppression of the starburst induced by the merger, so that our bursts are less intense than those produced in the simulations of, e.g., Mihos & Hernquist (1994, 1996) and Springel (2000). In our simulations, peak star formation rates for major mergers of typical late-type spiral galaxies are generally in the range 30–50 M\(_{\odot}\) yr\(^{-1}\), except for very short spikes.

Star formation in the simulations is treated using a stochastic scheme, in which gas particles are converted to collisionless stellar particles with a probability proportional to the star formation rate of the particle. This scheme avoids “hybrid” particles in which gas and stars are dynamically linked and instead has the effect of creating “super star clusters” as the gas particles have masses up to 10\(^6\) M\(_{\odot}\). Metal production is included in the simulations using an instantaneous recycling approximation, in which the metals produced by massive stars are deposited locally into the gas particle that gave birth to them. This scheme, along with the fact that recycling of gas by stellar populations was not included, can give rise to abnormally high metallicities in some of the gas particles, even though the total amount of metals produced is realistic (see also § 3.9).

Identical pairs of each of the seven galaxies in Table 1 were started on a parabolic orbit with the disks prograde. One of the disks was in the plane of the orbit, while the other was tilted by 30°. Eight additional mergers of the Sbc galaxies were also simulated, exploring variations in galaxy orientation and encounter orbit. Details about the merger initial conditions can be found in Appendix B of Cox (2004). Simulations of unequal-mass (minor) mergers have also been done (Cox 2004), but radiative transfer simulations of these have not yet been completed.

2.3. Radiative Transfer Model

The radiative transfer calculations are done using our new Monte Carlo code SUNRISE. A Monte Carlo code solves the
radiative transfer problem in a manner similar to how nature does it: “photons” are emitted from the luminous regions and are then scattered and/or absorbed depending on the opacity of the material they travel through. The external appearance of the simulation volume is determined by the rays that emerge, while those that are absorbed by the dust will be reemitted in the far-infrared. The main advantage of the Monte Carlo method is that it naturally handles complicated geometries without symmetries, although the computational requirements can be severe. In SUNRISE, the geometry of gas and stars along with the detailed star formation histories of the stellar particles are taken from the \(N\)-body simulations and used as inputs to the radiative transfer calculation. Outputs are multiwavelength images of the system from a number of viewpoints, as well as luminosity absorbed by dust and reradiated in the infrared. In these simulations, 11 different viewpoints, distributed isotropically on the unit sphere, were used. The code uses an algorithm similar to the DIRTY code (Gordon et al. 2001), and it is described in detail in Jonsson (2004) and in a future paper. SUNRISE is available to interested prospective users.\(^3\)

The SEDs used for the stellar emission were taken from the Starburst99 (ver. 4.0; Leitherer et al. 1999) stellar population synthesis model. The stellar initial mass function (IMF) used was similar to a Kroupa IMF (Kroupa 2002), with a high-mass slope of \(-2.35\) from the upper limit of 150 down to 1 \(M_\odot\). Below this mass it is flat down to the lower limit of 0.1 \(M_\odot\). The disk stars existing at the start of the simulation were assumed to have been forming at a uniform rate for the previous 8 Gyr. The bulge stars were assumed to have formed in an instantaneous burst 8 Gyr earlier. Because they are born in the high-density regions, young stellar particles formed during the simulation generally have small sizes. To avoid tracking these very small particles throughout the simulation, their sizes are assumed to grow with a velocity of 1 km s\(^{-1}\), up to a maximum size of 1 kpc. This is also consistent with a physical picture where these particles are thought of as young star clusters, which are unbound and disperse with a velocity of this order.

To be able to describe the simulation geometry with sufficient accuracy while keeping computational requirements reasonable, SUNRISE uses an adaptive grid to store the distribution of stellar emission and dust opacity. The base grid used was a \(5^3\) grid covering (200 kpc)\(^3\). Grid cells were then recursively subdivided into \(2^3\) subcells according to grid refinement criteria described in Jonsson (2004). The maximum number of recursive subdivisions used was 15, leading to a maximum grid resolution of \(\sim 1\) pc. (This is well below the gravitational resolution in the merger simulations, but individual SPH particles can have smoothing lengths this small.) The number of cells in the resulting grids range from around 70,000 at the start of the simulation to almost 300,000 at the time of peak star formation rate and highest densities.

The dust grain model used was the \(R = 3.1\) Milky Way model by Weingartner & Draine (2001) with a dust-to-metal ratio \(m_d/m_m = 0.4\) (Dwek 1998). A few simulations using the SMC (Small Magellanic Cloud) dust model were also done. The radiative transfer calculation was performed for 22 different wavelengths between 21 nm and 5 \(\mu\)m, including the H\(\alpha\) and H\(\beta\) nebular emission lines. One million Monte Carlo rays were traced for each wavelength. While the total dust luminosity is determined from the absorbed stellar luminosity by energy conservation, no self-consistent calculation of the infrared dust-emission spectrum is done. To estimate the far-infrared SED, we used the templates of Devriendt et al. (1999). These templates are based on a multicomponent dust model, in which the relative contributions of each component are adjusted to reproduce observed correlations between the total IR luminosity and the colors of IRAS galaxies at 12, 25, 60, and 100 \(\mu\)m. At each output time, we use the total dust luminosity \(L_{\text{IR}}\) predicted by our simulations to select the appropriate template.

As mentioned above, previous studies (Silva et al. 1998; Charlot & Fall 2000; Popescu et al. 2000) have shown that in order to reproduce observations of dust in spiral galaxies, it is necessary to invoke larger extinctions for the young stellar populations, generally interpreted as local absorption in the dense molecular “birth clouds.” It is worth noting that although this effect is not explicitly included in our simulations, it is implicitly at least partially present. As star formation rate increases with density, most stellar particles are born in high-density regions. The particles then gradually wander away from these regions with time, mimicking the effect of the gradual dissociation of stars from their birth clouds, even though real molecular clouds are far below the resolution of the simulations. Quantifying this effect is difficult because of the complicated density structure in the simulations. If the stellar particles are ordered by the opacity of the surrounding gas, 95% of the stellar particles younger than 10 Myr are located in more opaque regions than 50%–70% of the stellar particles that were present at the beginning of the simulation. The 95th percentile of these young stellar particles is located in regions \(10^2–10^4\) more opaque than the corresponding 95th percentile of the old stellar particles. These numbers apply once the starburst is underway; since the gas is initially homogenous, the difference is smaller early on.

3. RESULTS

In this section, we first present some general results from the radiative transfer simulations and then continue with the specific results concerning dust attenuation in the simulations. Throughout this paper, “attenuation” will be understood to refer to the fraction by which luminosity is decreased due to dust, either averaged over all directions or along a specific line of sight. The term attenuation is preferred over absorption to emphasize that both absorption and scattering processes in a complex geometry contribute to a net decrease (or, in rare cases, increase) in the emerging radiation.

3.1. Overview of a Major Merger

While the detailed behavior of a galaxy merger depends on the properties of the two galaxies and their encounter orbit, the general sequence of events is always qualitatively similar. Figure 1 shows the star formation rate of a merger between two Sbc galaxies, along with images of the system at different points in time. As the two galaxies initially approach each other, they are largely unaffected by each other’s presence. Tidal forces disrupt the galaxy disks at the time of the first close passage. The star formation rate then increases due to gas being driven inward as the galaxies separate. The star formation rate remains elevated as the galaxies turn around and again approach one another. At this stage, the star formation is widely distributed in the disks of the galaxies. There are several short bursts of centrally concentrated star formation as the two components merge. After coalescence, the merger remnant relaxes, and the star formation rate trails off over a timescale of about 1 Gyr.

At the end of this simulation, 47% of the gas has been turned into stars. Of the remaining gas, roughly 10% is in a star forming disk in the center of the remnant and about 45% is in cold

\(^3\) The Sunrise Web site is http://sunrise.familjenjonsson.org.
clumps at large radii, mostly associated with tidal debris. The remaining gas forms a hot halo around the remnant (Cox et al. 2004). In total, about 70% of the gas in the postmerger remnant is at radii larger than 50 kpc. The gas has been enriched from solar metallicity to an average metallicity of $1.4 Z_\odot$, while the stars formed during the encounter have an average metallicity of $1.7 Z_\odot$.

The evolution of the bolometric luminosity of the same simulation is shown in Figure 2. The bolometric luminosity of the system increases by almost an order of magnitude during the course of the merger, closely following the star formation rate, as expected for a starburst system in which young stars dominate the energy output. However, the fraction of luminosity that is absorbed by dust scales with luminosity in such a way that the luminosity not absorbed by dust typically stays almost constant. As the star formation rate, and hence the luminosity, increase, the column densities of gas and dust also go up, and with them the attenuation; the two factors appear to conspire to keep the UV/visual luminosity roughly constant. The origin of this effect is presumably that the majority of the young, luminous stars created in the merger are located in regions so heavily obscured that the UV/optical luminosity of the galaxy always is dominated by the older stars. The effect can be seen in Figure 2, where the solid lines, indicating luminosity escaping in different directions, show little variation with time. It was also observed by Bekki & Shioya (2000a) in their simulations, as well as in observational studies (Adelberger & Steidel 2000).

It is worth noting that the absorbed fraction of energy, which reaches about 90% during the final merger starburst, is surprisingly insensitive to the metallicity of the gas. Even in simulations in which the gas was given an initial metallicity of $0.2 Z_\odot$ and metal production was turned off, the peak attenuation reached 70%. This indicates that the final starburst occurs in very heavily obscured gas. Earlier in this simulation, while the two galaxies are still separate, the absorbed fraction is considerably lower. The star formation in these stages is distributed in the spiral disks, in much less obscured regions, so the absorbed fraction is more sensitive to the metallicity of the gas.

While there is little temporal variation in the luminosity not absorbed by dust, there is, in general, a substantial difference between the flux escaping in different directions. Because the initial systems consist of disk galaxies, radiation escapes preferentially out of the plane of the galaxies. This creates a difference of around a factor of 2 in the escaping flux, which is clearly visible in Figure 2. The merger remnant is more spheroidal, and thus the difference with viewing angle is smaller at the end stage of the mergers. As will be shown below, this variation in viewing angle means that quantities not dependent on direction, such as the fraction of bolometric luminosity that is absorbed, can be predicted with significantly smaller scatter than directional quantities such as the emerging luminosity in a specific direction.

3.2. Simulated Images and Spectra

As mentioned in the model description, the outputs from the radiative transfer calculations are multiwavelength images from a number of viewpoints or, more precisely, an SED for each pixel in the images. To facilitate comparisons with observations, these data cubes have been integrated into images in a number of broadband filters (listed in Table 3) covering wavelengths from the Galaxy Evolution Explorer (GALEX) FUV band to the IRAC2 band on the Spitzer Space Telescope, and also collapsed into a spatially integrated SED. In total, about 25 major-merger simulations have been run through the radiative transfer code, each at roughly 50 points in time. For each point in time, images and spectra have been generated from 11 viewpoints, equally distributed in solid angle, and in 12 different filters. This results in a grand total of roughly $10^5$ images and $10^4$ spectra. These images and spectra are not used in this paper, but to illustrate the
3.3. Comparing to Observations

In order to determine how well our simulations mimic actual starburst galaxies, they must be compared to observations. In terms of color and brightness, the simulations have an absolute $r$-band magnitude in the range $-21.5$ to $-22.5$ and a $u - r$ color of 1.3–2.2, falling in the region of bright, blue galaxies in the Sloan Digital Sky Survey (Baldry et al. 2004). Even 1 Gyr after the merger, there is enough ongoing star formation in the merger remnant that it remains among the blue galaxies. In recent simulations, Springel et al. (2005a, 2005b) have shown that feedback from an active galactic nucleus can help truncate star formation, which would make the merger remnant redden more quickly. In any case, the inclusion of dust is crucial for the agreement; without

outputs generated some images are shown in Figure 3 and a corresponding spectrum given in Figure 4.4

Movies and the full set of color images of the merger simulations can be found at http://sunrise.familjenjonsson.org/thesis.
it, the systems are about 1.2 mag brighter and 0.7 mag bluer, far too bright and blue to agree with observed galaxies. (These magnitudes refer to the entire system; no effort has been made to separate the galaxies.)

The simulations were also compared to observations by Meurer et al. (1999, hereafter MHC) and Heckman et al. (1998). Both of these studies looked at correlations between dust attenuation and other properties of starburst galaxies. MHC looked at the relation between dust absorption, indicated by the far-infrared over ultraviolet flux ratio, and the ultraviolet spectral slope. In a sample of moderately luminous starburst galaxies observed by the International Ultraviolet Explorer (IUE) and IRAS, they found a fairly tight correlation between the two parameters. However, Goldader et al. (2002) examined a small sample of more luminous LIRGs and ULIRGs and found that they depart from the relation seen by MHC in the sense that their UV color is too blue for their infrared luminosity. When the same quantities are extracted from the simulations, the dependence on luminosity, shown in Figure 5, is remarkably similar to what is observed. When similar-luminosity systems are selected, the simulated galaxies, while being somewhat too infrared bright, agree fairly well with the MHC relation. When the highest luminosity subsample of the simulated galaxies is selected, they are found in the same region as the LIRGs/ULIRGs of Goldader et al. (2002). In detail, the low-luminosity simulations have a different slope than the MHC relation at blue colors. Because the selection criteria used by MHC are not easily reproduced in the simulations, it is difficult to say whether this discrepancy is a problem for the simulations or whether it is simply a selection effect. It should be emphasized that the agreement is not a result of fitting the simulations to these observations, but rather a prediction of our initial conditions, which were chosen a priori to be realistic for local gas-rich spiral galaxies. Unlike in earlier studies that compared observed starburst galaxies to radiative transfer calculations (Gordon et al. 1997), this agreement is contingent on the use of Milky Way dust. Gordon et al. (1997) concluded that the far-ultraviolet colors of starburst galaxies was inconsistent with the presence of the “2200 Å feature” characteristic of Milky Way dust. However, in our simulations using SMC-type dust, the ultraviolet slopes are about 1.5 units too red, clearly inconsistent with the MHC relation.

The simulations have also been compared to the results of Heckman et al. (1998). This comparison can be found in Jonsson (2004). A more complete comparison between simulations and observations, including new results from GALEX and Spitzer, is planned for the future.

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Fig. 4.—SED associated with the second image of the Sbc-Sbc prograde-prograde major merger in Fig. 3, 1.6 Gyr into the simulation. The solid line shows the intrinsic stellar spectrum, while the dashed line shows the emerging spectrum after taking dust attenuation into account. At wavelengths longer than 5 μm, the dust emission spectrum is taken from the templates of Devriendt et al. (1999). The two emission lines in the optical are Hα and Hβ. In the ultraviolet, the dust attenuation is more than an order of magnitude, and the signature of the well-known 2200 Å bump in the Milky Way extinction curve is easily discernible. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 5.—Relation between the IR/UV flux ratio and the UV spectral slope for the Sbc merger simulations (shaded region), compared to the results from MHC (crosses) and Goldader et al. (2002) (diamonds and triangles). On the left, only simulated galaxies with bolometric luminosity $L_{bol} < 2 \times 10^{11} L_\odot$ have been included. This low-luminosity sample agrees fairly well with the MHC correlation, which is for galaxies in this luminosity range. On the right, only the highest luminosity simulated galaxies, with $L_{bol} > 7 \times 10^{11} L_\odot$, have been included. These points depart completely from the MHC galaxies and instead occupy the region of LIRGs/ULIRGs from the Goldader et al. (2002) sample. This agreement was not a result of fitting the models, but rather a prediction from our simulations, with no adjustment of parameters. This and other results indicate that our simulations provide a reasonably good replication of the properties of local starbursts.
3.4. Dust Attenuation

Looking at the nine Sbc simulations shown in Figure 6, there is a surprisingly tight correlation between the bolometric luminosity of the system and the bolometric dust attenuation, averaged over all directions. For a given bolometric luminosity a uniquely determined fraction of luminosity is absorbed by the dust; it does not seem to matter if the system consists of two barely interacting disks, a merger-driven starburst (on various orbits), or a post-starburst remnant. Simulations using galaxies of different mass or metallicity follow similar correlations offset to higher or lower attenuation.

Theoretically, it is expected that luminosity (for starbursting systems largely determined by the star formation rate) and dust absorption should correlate in the simulations, as both of these quantities are driven by gas density. Concentrating the gas to larger densities will increase the star formation rate, and hence the bolometric luminosity, through the Schmidt law used to estimate the star formation rate in the simulations, the star formation rate density is

$$\dot{\rho}_s \propto \rho^{3/2}. \quad (2)$$

The total star formation rate $\dot{M}_s$ is thus

$$\dot{M}_s \propto \dot{\rho}_s R^3 \propto M_g^{3/2} R^{-3/2}. \quad (3)$$

The optical depth of dust in the sphere will depend on the column density and the metallicity $Z$ of the gas,

$$\tau \propto Z \rho R \propto Z M_g R^{-2}. \quad (4)$$

Eliminating $R$ using equation (3), we get

$$\tau \propto Z \dot{M}_s^{4/3} M_g^{-1} \propto Z L^{4/3} M_g^{-1}, \quad (5)$$

where the last proportionality comes from assuming that the bolometric luminosity $L$ is proportional to the star formation rate. Finally, once the optical depth is determined, the absorbed fraction of luminosity (i.e., the attenuation) in a medium in which luminous and absorbing material is uniformly mixed is given by (e.g., Calzetti et al. 1994)

$$L_{\text{abs}}/L = 1 - (1/\tau)(1 - e^{-\tau}). \quad (6)$$

Actually, equation (6) is appropriate for a plane-parallel slab, not a sphere. However, the purpose of the toy model is to find a simple, physically motivated fitting formula. As is shown in the next section, equation (6) describes the behavior of the simulations well. Hence, in the interest of simplicity, it is used here.

This toy model has obvious limitations: It neglects scattering, and the exponents 4/3 and −1 depend on the assumed geometry. Furthermore, the model is really more representative of an individual star-forming region than an entire galaxy, so included in the constant of proportionality in equation (5) is the number of such regions in the galaxy. If this number depends on the properties of the galaxy, a reasonable assumption, it will change the dependence on the different quantities in equation (5). Finally, the attenuation of the bolometric luminosity is an average of the attenuation at all wavelengths, and because the system in general is optically thick at short wavelengths and more or less optically thin at longer wavelengths, the behavior is more complicated than the simple equation (6). Real galaxies are thus more complicated than our assumptions, but our simple model gives a general description of the trends for the effects of dust.

3.5. A Toy Model for Dust Attenuation

In order to come up with a simple model for how dust absorption should depend on the luminosity, mass, and metallicity of a galaxy, consider a constant-density sphere of star-forming gas. For a sphere, the density is given by

$$\rho \propto M_g R^{-3}, \quad (1)$$

where $M_g$ is the gas mass and $R$ is the radius. According to the Schmidt law used to estimate the star formation rate in the simulations, the star formation rate density is

$$\dot{\rho}_s \propto \rho^{3/2}. \quad (2)$$

The total star formation rate $\dot{M}_s$ is thus

$$\dot{M}_s \propto \dot{\rho}_s R^3 \propto M_g^{3/2} R^{-3/2}. \quad (3)$$

The optical depth of dust in the sphere will depend on the column density and the metallicity $Z$ of the gas,

$$\tau \propto Z \rho R \propto Z M_g R^{-2}. \quad (4)$$

Eliminating $R$ using equation (3), we get

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3.6. Fitting Functions

While $L \propto \dot{M}_s$ is a good approximation for starbursting galaxies, in which young stellar populations dominate the luminosity, this assumption is not valid in general. For this reason, simultaneous dependence on both $L$ and $M_s$ is retained.

Guided by the toy model, one would expect the gas mass to be the dominant factor in the relation. However, fits using total baryonic (gas plus stars) mass, $M_{\text{bary}}$ instead of gas mass, had lower residuals (see Table 2). The reason for this is not understood, but because of this baryonic mass is used for most of the fits.
Dependent on \( \dot{L} \), the scatter around the relation, one of the largely complimentary fits are appropriate if some of the quantities that are used are those of the system, implying that when the merging galaxies are still distinct, it is the aggregate luminosity absorbed by dust, it can be used to predict the dust luminosity of these systems. It should be emphasized that the dependence on the quantities is strange; \( \beta \) is negative, which means that more luminous galaxies should have smaller dust attenuation. It is as if luminosity has assumed part of the functionality of the baryonic mass.

Motivated by the toy model described above and these considerations, the general fitting function to be used for the simulations is equation (6), with the optical depth given by

\[
\tau = \tau_0 \left( \frac{Z}{0.02} \right)^{\alpha} \left( \frac{L}{10^{11} L_\odot} \right)^{\beta} \left( \frac{M_\star}{M_\odot \text{yr}^{-1}} \right)^{\gamma} \left( \frac{M_b}{10^{11} M_\odot} \right)^{\delta},
\]

where the Greek letters denote free parameters.

The fits were done as simple \( \chi^2 \) minimizations, with one point for each simulation snapshot in the simulations listed in Table 1. As there were nine different Sbc merger simulations and only one of each of the simulations using the other galaxy models, the Sbc simulations were given only \( \frac{1}{9} \) the weight in the fits. This was done to avoid giving undue weight to the massive, bright, and gas-rich Sbc mergers. Because the time between saved simulation snapshots was varied in order to capture short-lived stages, each simulation snapshot was also weighted in proportion to its “time of influence,” i.e., the time to preceding and following snapshots. Apart from this weighting, constant errors on the “time of influence,” i.e., the time to preceding and following snapshots. Apart from this weighting, constant errors on the fitted parameters could be associated with each point in time of a simulation.

Table 2 shows the parameters resulting from fits of the bolometric attenuation to the simulations under different constraints. The quantities appear with different powers from those in equation (5), but, as noted in § 3.5, this is not surprising.

A plot of the actual attenuations against those predicted from the full fit is shown in Figure 7. The fit describes the behavior of the simulations well, with a 1 \( \sigma \) scatter of about 0.04 in the absorbed fraction. Since this fit describes the fraction of bolometric luminosity absorbed by dust, it can be used to predict the dust luminosity of these systems. It should be emphasized that the quantities used are those of the system, implying that when the merging galaxies are still distinct, it is the aggregate luminosity, mass, and star formation rate of the two galaxies which is used.

Table 2 contains additional parameter sets besides the complete fit. These are appropriate if some of the quantities that go into equation (7) are unknown. With a modest increase in the scatter around the relation, one of the largely complimentary quantities \( L \) or \( M_\star \) can be excluded. In these cases, the power of the quantity not excluded increases to assume the role of the excluded quantity. With significantly increased scatter, the attenuation can also be predicted from one quantity only. This is presumably because metallicity, luminosity, and mass are intrinsically correlated in galaxies. It is difficult to say to what degree these single-parameter correlations are affected by our small set of galaxy models.

Finally, the last row of Table 2 contains the parameters obtained when the fit was done using the gas mass. The fit has about 50% larger scatter than when the baryonic mass was used, so it still provides a useful description of the data. However, the dependence on the quantities is strange; \( \beta \) is negative, which means that more luminous galaxies should have smaller dust attenuation. It is as if luminosity has assumed part of the function of the baryonic mass.

### 3.7. Fits at Specific Wavelengths

The fits in the previous section are useful for predicting the infrared dust luminosity of the systems, but they cannot be used to predict the attenuation of radiation emerging from the system observed at a specific wavelength. Furthermore, in order to be able to make predictions of the luminosity inferred by an observer, the variation in attenuation with line of sight must be considered. Table 3 contains fits, also using equation (7), to the attenuation in each of the bandpasses included in the calculation. Here, each point in time of a simulation is associated with 11 different attenuations, one for each of the different viewing angles calculated. These fits have significantly larger scatter than the fit to the bolometric attenuation in Table 2, but this is largely due to the variation of attenuation over different lines of sight. When the attenuation is averaged over all lines of sight, the fit is unchanged but the scatter is much smaller, only marginally larger than for the fit to bolometric attenuation. An example of a fit, for the SDSS \( g \) band, is shown in Figure 8.

### 3.8. Observations of Dust Attenuation

Several previous studies have attempted to estimate the dust attenuation in observed galaxies, and our simulations can be compared to these results. Wang & Heckman (1996, hereafter WH96) examined the dust content in late-type galaxies based on their UV/FIR flux ratio and fit the derived optical depth to a power-law dependence on luminosity. Their fit was also based on a model of a uniformly mixed slab of stars and dust, so comparing our simulations to the WH96 results should be

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**Table 2**

| Fit                          | \( \tau_0 \) | \( \alpha \) | \( \beta \) | \( \gamma \) | \( \delta \) | \( \sigma^b \) |
|------------------------------|--------------|--------------|-------------|-------------|-------------|---------------|
| Full fit                     | 1.25         | 1.02         | 0.41        | 0.39        | -0.82       | 0.04          |
| Independent of \( L \)       | 0.93         | 1.10         | 0.61        | -0.68       | 0.04        |
| Independent of \( M_\star \) | 2.10         | 0.91         | 1.10        | -1.03       | 0.05        |
| Dependent on \( Z \) only    | 2.09         | 0.94         | 0.28        | 0.10        |
| Dependent on \( L \) only    | 2.34         | ...          | 0.28        | 0.10        |
| Dependent on \( M_\star \) only | 1.70    | ...          | 0.26        | 0.10        |
| Dependent on \( M_b \) only  | 2.21         | ...          | ...         | 0.16        | 0.16        |
| Full fit with \( M_\star \)   | 0.32         | 0.30         | -0.15       | 0.82        | -0.52       | 0.05          |

**Note.** — The attenuation is the fraction of bolometric luminosity that is absorbed, averaged over all directions.

\( a \) Parameter in eq. (7).

\( b \) The standard deviation of the scatter around the fit.

\( a \) This fit was performed with gas mass, instead of baryonic mass, driving the parameter \( \delta \) in eq. (7).

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**Figure 7**

Actual attenuation (fraction of bolometric luminosity absorbed by dust) in the simulations compared to the attenuation predicted by the full fit of eq. (7) (the first row of Table 2). Each point is a simulation snapshot.
straightforward. To make the comparison, a fit of the ultraviolet luminosity (i.e., with $\alpha = \gamma = \delta = 0$), shown in Figure 9, was performed. This fit was complicated by the fact that when using only luminosity, instead of all parameters, to predict the dust attenuation, there is a significant difference between the initial merging galaxies and the merger remnants. Especially in the smaller G2, G1, and G0 mergers, the merger remnants have significantly higher dust attenuation for their luminosity compared to the earlier stages. Furthermore, because the simulated galaxies spend a lot of time as merger remnants (limited only by how long the simulation has been run), this stage has significant weight when fitting. These points can be seen in the top left of Figure 9a. As discussed below, our model likely overestimates the dust attenuation in the merger remnants. For this reason, and also because WH96 did not include early-type galaxies, the low-luminosity, high-attenuation points in the delineated region in the top left of Figure 9a were excluded in this fit. (If these points are included, the resulting fit, also shown in Fig. 9a, does not provide a good description for the low-luminosity premerger and merging galaxies.)

After excluding these points, the fit yields $\beta = 0.70$, consistent with the luminosity dependence in WH96, who obtained $\beta = 0.5 \pm 0.2$. In terms of the normalization, our fit results in $\tau_0 = 23.9$, at a luminosity of $10^{11} L_\odot$. Rescaled to the WH96 luminosity zero point of $4.5 \times 10^9 L_\odot$, it corresponds to a UV optical depth of 2.7. The WH96 result was $1.7 \pm 0.6$, but this is the face-on optical depth. Our results are averaged over all viewing angles (it is not even clear what face-on means for the merging systems) and WH96 states that the angle-averaged optical depth is roughly equal to twice that of the face-on view. Taking this factor of 2 into account, our simulations are consistent with the WH96 result.

It is obvious from Figure 9 that the scatter in this fit, compared to the fits using metallicity, star formation rate, and mass, is very large. This reflects the fact that luminosity is not the only factor determining the dust attenuation. For example, a galaxy that is bright because it is massive and a galaxy that is bright because it is undergoing a vigorous starburst will have different dust attenuations. This intrinsic scatter is obvious also for the observed galaxies, which show a scatter of an order of magnitude in the UV/FIR flux ratio for a given luminosity. Unfortunately, this large scatter also means that the fits can be influenced significantly by selection effects, which have not been taken into account in this comparison.

WH96 also presented their results in terms of the $B$-band luminosity and, correspondingly, the attenuation in the $B$ band. To compare to these results, a fit to the simulations was done in the $B$ band (using the prescription of Fukugita et al. [1996] to transform the SDSS magnitudes into a $B$ magnitude). The same

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**TABLE 3**

| Filter       | $\tau_0^a$ | $\alpha^a$ | $\beta^a$ | $\gamma^a$ | $\delta^a$ | $\sigma^b$ | $\sigma^c$ |
|--------------|------------|-----------|----------|-----------|----------|-----------|-----------|
| GALEX FUV    | 7.67       | 3.33      | -0.04    | 0.29      | -0.74    | 0.07      | 0.04      |
| GALEX NUV    | 5.03       | 2.45      | 0.03     | 0.36      | -0.61    | 0.07      | 0.04      |
| SDSS $g$     | 1.84       | 1.52      | 0.45     | 0.28      | -0.70    | 0.10      | 0.05      |
| SDSS $r$     | 1.27       | 1.39      | 0.55     | 0.19      | -0.70    | 0.11      | 0.05      |
| SDSS $i$     | 0.94       | 1.36      | 0.61     | 0.16      | -0.71    | 0.12      | 0.05      |
| SDSS $z$     | 0.78       | 1.34      | 0.65     | 0.12      | -0.70    | 0.11      | 0.05      |
| 2MASS $J$    | 0.68       | 1.37      | 0.69     | 0.10      | -0.72    | 0.11      | 0.05      |
| 2MASS $H$    | 0.53       | 1.43      | 0.72     | 0.09      | -0.74    | 0.10      | 0.05      |
| 2MASS $K$    | 0.42       | 1.54      | 0.76     | 0.09      | -0.78    | 0.09      | 0.05      |
| Spitzer IRAC1| 0.19       | 1.78      | 0.74     | 0.14      | -0.82    | 0.06      | 0.04      |
| Spitzer IRAC2| 0.14       | 1.95      | 0.71     | 0.18      | -0.86    | 0.06      | 0.04      |
| 1900 Å (WH96)$^d$ | 23.9 | ... | 0.70 | ... | ... | 0.12 | 0.10 |
| $B$ (WH96)$^d$ | 4.0      | ... | 0.49 | ... | ... | 0.15 | 0.11 |

**Notes.**—Fits were performed using all parameters. The scatter in the far-ultraviolet bands is suppressed because most attenuations are close to 1.

* $a$ Parameter in eq. (7).

* $b$ The standard deviation of the total scatter around the fit, including the variation with viewing angle.

* $c$ The standard deviation of the intrinsic scatter around the fit, i.e., excluding the variation with viewing angle.

* $d$ Fits done as a comparison to the study by Wang & Heckman (1996), described in § 3.8.

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![Fig. 8.—Actual attenuation in the simulations vs. the attenuation predicted by eq. (7) but now for the luminosity in the Sloan Digitized Sky Survey $g$ band. Unlike Fig. 7, which shows absorbed energy averaged over all lines of sight, this figure shows the line-of-sight attenuation. Each point is a simulation snapshot from a certain line of sight. The slightly negative attenuations result from preferential scattering out of the plane of the disk in the initial galaxies. This fit has significantly larger scatter than the fit to bolometric attenuation, mainly because of the large variation of attenuation with viewing angle, but it provides a good description of the behavior averaged over all directions.](image-url)
points were excluded for this fit, also shown in Figure 9, as for the ultraviolet fit. This results in \( \beta = 0.49 \). For the normalization, our result was \( \tau_0 = 4.0 \), which, rescaled to the WH96 luminosity of \( 1.3 \times 10^{10} L_\odot \), corresponds to an optical depth of 1.5. Their result was \( 0.8 \pm 0.3 \), so, given the factor of 2 conversion from face-on to angle-averaged optical depth, our simulations are consistent with WH96 also in the \( B \) band. It is important to note that WH96 simply converted their UV optical depth to \( B \)-band, while we performed an actual fit to the \( B \)-band attenuation. These methods should not give the same result if the population of stars giving rise to the attenuation in the \( B \) band is different from those responsible for the UV attenuation. That this is the case is indicated by the fact that our fits have different luminosity dependence in the different bands.

A similar study was performed by Vijh et al. (2003), who estimated the UV attenuation in a sample of Lyman break galaxies using radiative transfer models of clumpy dust shells. They obtained

\[
1 - \frac{L_{\text{abs}}}{L} \propto L^{-0.95 \pm 0.5},
\]

at 1600 Å. In optically thick situations, this would correspond to \( \beta = 0.95 \pm 0.5 \) in our formulation, also consistent with our result at 1900 Å.

Buat et al. (2005) compared the dust attenuation, in the \textit{GALEX} near-UV (NUV) band, of two samples selected in the near-ultraviolet and far-infrared. While they saw an increase in dust attenuation with luminosity in both samples, they did not attempt to determine the luminosity dependence. No attempt has been made to replicate their selection criteria in our simulated galaxies either, but the distribution of attenuation with luminosity in the simulations (shown in Fig. 10) is similar to that of their sample.

### 3.9. Model Limitations

While our simulations try to self-consistently model the evolution of dust attenuation along with star formation rate and luminosity in starbursts, our model has limitations. For one, even though our simulations include the phenomenon that stars are born in regions with higher than average density, these regions are not resolved. If these regions had been resolved, the resulting concentrations of dust and stars on even smaller scales would have the effect of making the dust hotter and changing the dust emission spectrum. Because of this, it is reasonable to expect a

Fig. 9.—Comparison with WH96. \textit{Left}: Attenuation at 1900 Å vs. luminosity at 1900 Å for the simulations. \textit{Right}: Attenuation in the \( B \) band vs. luminosity in the \( B \) band. The size of the symbols are proportional to the fitting weight of the points. The dashed lines show the fits marked “WH96” in Table 3. The points in the top left region in the left plot, marked by the solid line, consist of merger remnants and were excluded from the fit for reasons explained in § 3.8. Because these points are not nicely delineated in the right plot, they are also marked as crosses. (The dotted lines show the fits obtained if these points are included in the fit.) The dot-dashed lines show the WH96 fits, plotted by inserting their \( \tau_0 \) in eq. (6). The fits to the simulated galaxies agree with the WH96 fits within their stated errors once the WH96 face-on optical depths have been converted to optical depths averaged over all angles, as described in the text. In the \( B \) band, the agreement is excellent, while in the UV the simulations are less attenuated than the WH96 galaxies at low luminosities. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 10.—Luminosity absorbed by dust vs. attenuation in the \textit{GALEX} NUV band (in magnitudes) for the simulated galaxies. This plot can be directly compared to Fig. 3 of Buat et al. (2005). Their IR-selected galaxy sample shows a very similar distribution, while their UV-selected sample has lower attenuations. Given that our simulated galaxies are bright starbursts, the infrared selection is likely more appropriate, at least at higher luminosities. For \( L_{\text{abs}} < 10^{10} L_\odot \), the Buat et al. (2005) IR-selected sample contains very few galaxies, probably due to a selection effect, but the ones present lie in the same region as the simulations.
deficit of warm dust emission from our simulations if the infrared SED had been calculated. It is also likely that concentrating the dust into smaller regions would lead to a higher attenuation of the recently formed stars in comparison to the older population.

Furthermore, molecular clouds are known to be clumpy or patchy, but this is not taken into account in the simulations. Previous studies (Witt & Gordon 1996, 2000) have indicated that the structure of star-forming regions has important implications for their obscuring characteristics. The most noticeable effect of such clumping would be “holes” with lower attenuation, so that our simulations would underestimate the frequency with which young stellar populations are visible.

Another phenomenon that is treated poorly in our simulations is gas outflows. Starburst galaxies are almost ubiquitously observed to have large-scale gas outflows (e.g., Heckman et al. 2000). While our feedback prescription does provide supernova energy input into the ISM, it does not seem to lead to significant outflows. This is a well-known problem in SPH simulations; the real ISM has a multiphase structure, which is not captured by the limited resolution of the simulations, and the gas is locked in fairly massive particles that have difficulty climbing out of the potential well. (An attempt to overcome this problem was made by Springel & Hernquist 2003.) Furthermore, recent simulations including active galactic nuclei (AGNs; Springel et al. 2005b) show that AGN feedback can drive a powerful outflow, clearing out gas from the central regions of the galaxies. Since our simulations do not include AGNs, this source of outflows is also not included in our present simulations. In the context of dust attenuation, this lack of outflows has two implications. First, winds, like small-scale dust patchiness, would tend to open up holes in the dust distribution. Second, the lack of outflows also means that the metals produced by the starburst remain in the starburst region.

This is exacerbated by the metal production scheme used in the simulations, in which metals are deposited locally and do not diffuse into surrounding regions. Only Type II supernovae are included, and since Type I supernovae only occur after a substantial time delay, including these would likely lead to the deposition of energy and metals in less dense regions. Also, even though a stellar population recycles a substantial fraction of its hydrogen and helium during its lifetime, this is not included in the simulations. Finally, in a cosmological context, we would expect a substantial inflow rate of fresh gas over the timescale of the simulations. All of these caveats have the effect of making the metals more concentrated and leading to abnormally high metallicities in some regions. Since the optical depth is determined using a constant dust-to-metal ratio, this will translate to a larger opacity within the star-forming regions than would be expected if a significant fraction of the metals were ejected or deposited elsewhere. More ambitious models for metal enrichment have been developed (Mosconi et al. 2001; Tornatore et al. 2004; Scannapieco et al. 2005), and we intend to improve our simulations to address these problems.

Another limitation of the model that would lead to an overestimate of the attenuation is the lack of a realistic metallicity gradient in the model galaxies. Sbc galaxies are observed to have a metallicity that decreases on the order of 0.05 dex kpc$^{-1}$ (Zaritsky et al. 1994). Including such a gradient would make the scale length of the dust smaller than the scale length of the gas, more in line with studies of the dust scale length in edge-on spirals, which indicate that the dust scale length only is slightly larger than the stellar scale length (Xilouris et al. 1999). Preliminary simulations of an isolated Sbc galaxy with a metallicity gradient of 0.03 dex kpc$^{-1}$, the value that makes the dust scale length agree with the results of Xilouris et al. (1999), have been performed. In these simulations, the bolometric attenuation is lowered from 46% to 37%, in better agreement with but still higher than observations of Sbc galaxies in the Virgo Cluster (Popescu & Tuffs 2002). It is unclear how this lowered attenuation would affect the agreement with WH96.

Given these limitations, it is probable that our simulations overestimate the amount of dust attenuation to some degree. However, the agreement with the Wang & Heckman (1996) results seems to indicate that the overall attenuation as a function of galaxy properties is approximately correct at least in the initial stages of the simulations (which are the most appropriate to compare with these observations). It is also not clear whether overcoming these limitations would change our basic conclusions, in particular, the functional form of the relationship between galaxy properties and attenuation that we have presented. For example, while an AGN-driven outflow will clear out gas and dust from the galaxy and hence decrease the dust attenuation, it also truncates star formation. Thus, while the evolution of the (stellar) luminosity of the starburst would be altered by this phenomenon, the correlation between dust attenuation and the luminosity, metallicity, etc., of the starburst given by equation (7) would not necessarily be altered. Work is underway to improve our model and include many of these effects.

4. DISCUSSION

One of the remarkable aspects of Figure 6 is the overlap between the low-luminosity stages of the simulations, which comprise both the initial, separate, and relatively gas-rich spiral galaxies, and the final relatively gas-poor, spheroidal merger remnants. A priori, there seems to be no reason to expect that the attenuation should remain constant if two galaxies are merged into one. However, from the fit results in Table 2 it is evident that the powers of the extensive quantities $L$, $M$, and $M_b$ approximately add to zero. This results in a dust attenuation that is almost insensitive to simple size scaling of the galaxies; rather than being determined by luminosity or star formation rate alone, the dust attenuation seems to be governed by “specific luminosity” and “specific star formation rate,” i.e., $L/M_b$ and $M_*/M_b$. This is fortunate for our analysis, since it means that not treating the two galaxies in the initial stages of the merger separately does not bias the results. This is only true in the specific case being treated here, where the two galaxies are identical. If the two galaxies were not identical, as when simulating minor mergers or a merger between a spiral and an elliptical galaxy, the dust attenuation would have to be determined separately for the two components regardless of whether $\beta, \gamma$, and $\delta$ sum to zero.

It should, however, be pointed out that $\beta + \gamma + \delta \approx 0$ is a poor approximation for the fits to the attenuation in the GALEX bands in Table 3. There is thus the possibility that the fits in these bands have been biased by our use of system, rather than individual galaxy, quantities. Indeed, there is a significant discrepancy between the fits and the initial stages of the simulations in these bands, such that the fits overestimate the amount of dust attenuation.

Looking at the parameter sets in Table 3, clear trends with wavelength can be seen. Going from ultraviolet to near-infrared wavelengths, the dependence on star formation rate decreases while the dependence on luminosity increases. This is not unexpected; the luminosity in the ultraviolet is dominated by massive, short-lived stars, and hence correlates well with star formation rate. At longer wavelengths, contributions to the luminosity come from stars of a wide range in age and it is better represented by the bolometric luminosity of the galaxy. This trend with wavelength
thus contains information about the stars whose radiation is being absorbed. What is more surprising is that the trend is reversed at wavelengths longer than 2 μm. Naively, one would expect that the dust attenuation at progressively longer wavelengths always would be more dominated by older stars, but this does not seem to be the case. This effect probably originates in the fact that around the age of 10 Myr, a stellar population is very bright in the near-infrared due to the presence of red supergiants. The luminosity at several microns is contributed by young, intermediate-age, and older stars, contrary to what is expected from their main-sequence temperatures alone.

It was earlier noted that, as shown in Figure 2, the UV/visual luminosity not absorbed by dust is essentially independent of the intrinsic bolometric luminosity. This notion is confirmed by the fit to the bolometric attenuation independent of the star formation rate in Table 2. That fit yielded $\beta = 1.10$, close to $\beta = 1$, for which the increase in luminosity is exactly compensated by the increase in attenuation given by equation (6) (in the optically thick limit).

Does the fact that the dust attenuation in the simulations is well described by equation (6) indicate something about the relative geometry of dust and stars in the simulations? As already mentioned, gas density is the driving factor behind both dust optical depth and star formation rate. Furthermore, in the simulations, dust and stars are assumed to be uniformly mixed within individual grid cells. It is thus not unreasonable to expect that a uniform mixture of dust and stars should fit the simulations reasonably well.

The fact that the dust attenuation can be predicted so well by a simple formula has interesting implications for the question of what physical factors determine whether a luminous galaxy will be a ULIRG or not. Bekki & Shioya (2000b), from analyzing a prograde-prograde and a retrograde-retrograde major merger at the time of highest star formation rate, drew the conclusion that retrograde mergers should have stronger internal dust attenuation than prograde ones. This led them to conjecture that interacting galaxies without long tidal tails should be more prevalent among ULIRGs. This result is not confirmed by our much more extensive analysis. While there is a tendency for retrograde mergers to induce slightly more intense starbursts in our simulations, and hence be more obscured according to our fitting formula, they follow the same relation for dust attenuation as mergers of any other geometry. At least within the parameter space covered by these simulations, there should be no such thing as a “naked” vigorously star-forming, $10^{12} L_\odot$ system. While the attenuation along some lines of sight might be smaller, the vast majority of the bolometric luminosity should always be emerging as infrared dust emission.

Comparing these simulations to the studies of Wang & Heckman (1996) and Vijh et al. (2003), it is encouraging to note that the dependence of optical depth on luminosity is similar and the normalization is approximately correct. Unfortunately, these observational studies did not consider metallicity or mass information, so they were unable to perform a multidimensional fit like the one in this study. It would be interesting to know whether the dependence on these parameters would also be similar to what is found here.

The fitting formulae presented here are in the “theoretical plane,” i.e., they depend on quantities such as total baryonic mass and bolometric luminosity, which are generally known in theoretical models but are hard to determine from observations. It has already been emphasized that dust effects cancel the effects of increased luminosity to a remarkable degree, so that the simulations show virtually no correlation between the apparent luminosity and the dust attenuation, either bolometric or in the ultraviolet. Unfortunately, this implies that using our fitting functions to draw conclusions about these highly dust-extinguished systems from their apparent UV/optical luminosity is very difficult unless infrared data are available. In particular, “correcting” apparent luminosities for dust using luminosity-based prescriptions, like our fitting functions, is not likely to work well. This fact was also noted by Hopkins et al. (2001).

The relations presented here should be suitable for inclusion in theoretical models for galaxy formation, such as semianalytic models (SAMs) including merger-driven starbursts (e.g., Somerville et al. 2001). Unlike other theoretical models of dust attenuation, our results predict the magnitude of the dust attenuation and its dependence on the properties of the galaxy, over a large range of galaxy masses and luminosities, using a simple fitting formula. Current approaches used to incorporate dust in SAMs include relying on empirical results like those of WH96 (Somerville & Primack 1999; Kauffmann et al. 1999) or even simpler approximations, such as a uniform slab with optical depth proportional to gas column density times metallicity, essentially the toy model presented here (Cole et al. 2000; Devriendt & Guiderdoni 2000). Even in SAMs with more sophisticated models for inclusion of dust, such as those of Granato et al. (2000), the optical depth is typically determined in the same simple way. These models also contain numerous adjustable parameters whose values are not predicted by the SAM and thus must be assumed. Given that our fits appear to work well across a wide range of galaxy properties, including these results in SAMs should lead to a more realistic estimation of the effects of dust in cosmological scenarios.

Finally, nothing has been said here about the shape of the dust attenuation curve, e.g., if the simulated galaxies obey the Calzetti law (Calzetti et al. 1994). This information is contained in our fits, and a future paper will explore this in detail. For now, we simply remark that our simulations are inconsistent with a simple “screenlike” attenuation curve like the Calzetti law and do not even follow any single reddening law resulting from more complicated geometries (Witt & Gordon 1996; Gordon et al. 1997; Pierini et al. 2004; Tuffs et al. 2004). This is likely the result of a stochastic superposition of many star-forming regions with various optical depths and ages.

5. SUMMARY

We have presented results from radiative transfer calculations in an extensive suite of galaxy major-merger simulations. The results from these simulations consist of images at many different UV/optical/NIR wavelengths, as well as SEDs. We show that these simulations, with no tuning, reproduce the observed correlation between the UV spectral slope and the fraction of light absorbed by dust (the IRX-$\beta$ relation of MHC), as well as the optical depth as a function of galaxy optical luminosity (WH96).

Our main result is that the dust attenuation (defined as the fraction of luminosity that is absorbed by dust) in the simulations can be predicted from the bolometric luminosity, star formation rate, baryonic mass, and average gas metallicity of the system through a simple, physically motivated formula (eq. [7]). We present fitting formulae for the bolometric attenuation as well as the attenuation in various wavebands from the far-ultraviolet to the near-infrared. Averaged over all directions, the attenuation of the bolometric luminosity can be predicted with a scatter of 4%. The attenuation along a specific line of sight can be predicted with a scatter of 6%–12%, depending on wavelength. The increased scatter is largely a result of the variation of attenuation with viewing angle. These relations are valid for simulations with a range of 2 orders of magnitude in mass, with metallicities from 0.3 to 1.1 Z_\odot and gas.
fractions from 20% to 50%. The relations also seem to be valid in simulations of both isolated and interacting galaxies.

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