Simulations of Dust in Interacting Galaxies

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Abstract. A new Monte-Carlo radiative-transfer code, Sunrise, is used to study the effects of dust in N-body/hydrodynamic simulations of interacting galaxies. Dust has a profound effect on the appearance of the simulated galaxies. At peak luminosities, \( \sim 90\% \) of the bolometric luminosity is absorbed, and the dust obscuration scales with luminosity in such a way that the brightness at UV/visual wavelengths remains roughly constant. A general relationship between the fraction of energy absorbed and the ratio of bolometric luminosity to baryonic mass is found.

Comparing to observations, the simulations are found to follow a relation similar to the observed IRX-\( \beta \) relation found by Meurer et al. [1] when similar luminosity objects are considered. The highest-luminosity simulated galaxies depart from this relation and occupy the region where local (U)LIRGs are found. This agreement is contingent on the presence of Milky-Way-like dust, while SMC-like dust results in far too red a UV continuum slope to match observations.

The simulations are used to study the performance of star-formation indicators in the presence of dust. The far-infrared luminosity is found to be reliable. In contrast, the H\( \alpha \) and far-UV luminosity suffer severely from dust attenuation, and dust corrections can only partially remedy the situation.

INTRODUCTION

Galaxy mergers are an important ingredient in the hierarchical picture of galaxy formation. They transform disks to spheroids, and may have been responsible for forming a majority of the stars in the Universe [2]. Interacting galaxies are also triggering the most luminous starbursts in the Universe, in the Luminous and Ultraluminous Infrared Galaxies. Numerical simulations have been used to study interacting galaxies and the resulting starbursts [3, 4], but these simulations alone cannot predict what these objects would look like to observers, as the spectacular bursts of star formation in (U)LIRGS are completely hidden by interstellar dust. Calculating the effect of dust in galaxies is complicated. The mixed geometry of stars and dust makes the dust effects geometry-dependent and nontrivial to deduce. Because of this, a full radiative-transfer model is necessary to calculate these effects realistically. Previous studies of dust in galaxies have, with few exceptions [5, 6], not used information from hydrodynamic simulations. This study applies a new Monte-Carlo radiative-transfer code, Sunrise, to the outputs from a comprehensive suite of N-body/hydrodynamic simulations of merging galaxies [7].

The N-body simulations of merging galaxies consist of a comprehensive suite of hydrodynamic simulations using the GADGET N-body/SPH code. The simulations study the effects of merger mass ratio, encounter orbit, and progenitor galaxy structure, as well as different star-formation and feedback prescriptions, on the ensuing starburst and the structure of the merger remnant [7]. The merging galaxies have been modeled to closely resemble observed spiral galaxies in the local Universe.
from this study include the discovery of a shock-driven gas outflow from some merging systems [8] and an improved measure of how the intensity of the starburst scales with merger mass ratio in minor mergers. Our simulations also show how a disk reforms after the merger event, as in simulations by Springel and Hernquist [9].

For mergers with mass ratios smaller than 1:5, there is little induced star formation. Also, major mergers of smaller progenitor galaxies have fundamentally different star-formation properties than larger ones, with larger and more prolonged enhancements of star formation due to the merger event. Our suite of merging galaxy simulations is by far the largest performed so far.

RADIATIVE-TRANSFER MODEL

In order to calculate the effects of dust in these simulations, a new Monte-Carlo radiative-transfer code, Sunrise, was developed [10]. The geometry of stars and gas in the N-body simulations and the star-formation history of the system are used as inputs to the radiative-transfer calculation. To make calculations with such complicated geometries feasible, Sunrise features an adaptive-mesh refinement grid and is shared-memory parallel. For the stellar emission, SEDs from the Starburst99 population synthesis model [11] are used. The dust model is taken from Weingartner and Draine [12], and dust is assumed to trace metals in the simulations. Currently, the infrared dust emission is not calculated self-consistently. Instead, the infrared templates of Devriendt et al. [13] are used. A self-consistent dust emission calculation is planned for the future. In addition to using N-body simulations as inputs, the code can be used to solve problems specified in other ways. As a service to the community, Sunrise is being released to the public under the GNU General Public License1.

SIMULATION RESULTS

Radiative-transfer calculations of over 20 simulated disk-galaxy major mergers have been completed, resulting in over 11,000 simulated images and spectra [10]. Example images are shown in Figure 1, and movies of entire merger simulations are available on the Internet2. A smaller number of simulations of the isolated progenitor galaxies have also been done.

The radiative-transfer calculations show that dust has a profound effect on the appearance of the simulated systems. At the most luminous phase of the merger, $\sim 90\%$ of the bolometric luminosity is absorbed by dust. The dust attenuation scales with luminosity in such a way that the brightness at UV/visual wavelengths remains roughly constant throughout the merger event, even though the bolometric luminosity of the system increases by a factor of 4 due to the merger-driven starburst. A general relationship

1 The Sunrise web site is http://sunrise.familjenjonsson.org.
2 http://sunrise.familjenjonsson.org/thesis
FIGURE 1. Images of a simulated late-stage galaxy merger showing, from left to right, GALEX FUV band, SDSS $r$ band and infrared dust emission. Because the radiative-transfer model currently does not calculate a spatially dependent infrared SED, the IR image corresponds to bolometric dust luminosity. The images cover 100 kpc. While the UV/visual images show a peculiar, obviously dusty, galaxy, the IR image shows that the cores of the progenitor galaxies are still distinct and vigorously star forming. Images like these can be compared to observations of interacting systems.

FIGURE 2. The IRX-β relation of the simulations (shaded region), compared to the results from Meurer et al. [1, crosses] and Goldader et al. [14, diamonds/triangles]. On the left, only simulated galaxies with bolometric luminosity $L_{\text{bol}} < 2 \cdot 10^{11} L_{\odot}$ have been included. This low-luminosity sample agrees fairly well with the MHC correlation. On the right, only the highest-luminosity simulated galaxies, with $L_{\text{bol}} > 7 \cdot 10^{11} L_{\odot}$ have been included. These points depart completely from the MHC galaxies and instead occupy the region of (U)LIRGs from the Goldader et al. [14] sample.

between the fraction of energy absorbed and the ratio of bolometric luminosity to baryonic mass is found to hold in galaxies with metallicities $> 0.7 Z_{\odot}$ over a factor of 100 in mass.

The accuracy with which the simulations describe observed starburst galaxies is evaluated by comparing them to observations by Meurer et al. [1] and Heckman et al. [15]. The simulations are found to follow a relation similar to the IRX-β relation found by Meurer et al. [1] when similar luminosity objects are considered. The highest-luminosity simulated galaxies depart from this relation and occupy the region where local (U)LIRGs
are found. These results are shown in Figure 2. Comparing to the Heckman et al. [15] sample, the simulations are found to obey the same relations between UV luminosity, UV color, IR luminosity, absolute blue magnitude and metallicity as the observations. This agreement is contingent on the presence of a realistic mass-metallicity relation, and Milky-Way-like dust. In contrast with earlier studies [16], SMC-like dust results in far too red a UV continuum slope to match observations. On the whole, the agreement between the simulated and observed galaxies is impressive considering that the simulations have not been fit to agree with the observations, and we conclude that the simulations provide a realistic replication of the real universe.

The simulations are then used to study the performance of star-formation indicators in the presence of dust. The far-infrared luminosity is found to be a reliable tracer of star formation, as long as the star-formation rate is larger than about 1 \(M_\odot/\text{yr}\). In contrast, the \(H\alpha\) and far-ultraviolet luminosities suffer severely from dust attenuation, as expected. Published dust corrections based on the Balmer line ratios [17] or the ultraviolet spectral slope [18] only partially remedy the situation, still underestimating the star-formation rate by up to an order of magnitude.

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