Photo-Dynamic Models of Isolated and Merging Galaxies

Joshua Barnes
Lisa Chien

Astronomy Department, Kyoto University
July 14, 2008
Why Bother?

Most stars are old; little extinction.

Young + old stars; some extinction.

Ongoing starburst; high extinction.
SIMULATIONS OF DUST IN INTERACTING GALAXIES. I. DUST ATTENUATION

Patrik Jonsson
Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064; patrik@ucolick.org

T. J. Cox\(^1\) and Joel R. Primack
Department of Physics, University of California, Santa Cruz, CA 95064; tcox@cfa.harvard.edu, joel@scipp.ucsc.edu

AND

Rachel S. Somerville\(^2\)
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; rachel@mpia-hd.mpg.de

Received 2005 March 6; accepted 2005 August 26

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 \(\sim 90\%\) 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-\(\beta\)) 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
Collisionless Stellar Dynamics

Collisionless Boltzmann Equation (CBE) and Poisson Equation:

\[
\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{r}} - \nabla \Phi \cdot \frac{\partial f}{\partial \vec{v}} = 0 \quad \nabla^2 \Phi = 4\pi G \int d^3\vec{v} f(\vec{r}, \vec{v}, t)
\]

N-Body (Monte-Carlo) representation:

\[
f(\vec{r}, \vec{v}) \rightarrow \{(m_i, \vec{r}_i, \vec{v}_i) \mid i = 1, \ldots, N\}
\]

\[
\frac{d\vec{r}_i}{dt} = \vec{v}_i \quad \frac{d\vec{v}_i}{dt} = \sum_{j \neq i}^N \frac{G m_j (\vec{r}_j - \vec{r}_i)}{(|\vec{r}_j - \vec{r}_i|^2 + \varepsilon^2)^{3/2}}
\]

Hierarchical “Tree” code:

\[
\sum_{i}^{N} \rightarrow \sum_{c}^{N_c} \quad N_c \simeq O(\log N)
\]

Barnes & Hut (1986)
Interstellar Medium Dynamics

ISM model: compressible fluid with isothermal EOS \(( P = c_s^2 \rho )\)

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = -\nabla \Phi + \frac{1}{\rho} \nabla P
\]

Smoothed Particle Hydrodynamic (SPH) representation:

\[
\rho(\vec{r}), \vec{v}(\vec{r}) \rightarrow \{(m_i, \vec{r}_i, \vec{v}_i) \mid i = 1, \ldots, N\}
\]

\[
\rho_i = \sum_j^{N_n} m_j \overline{W}_{ij}(r_{ij}) = \sum_j^{N_n} \frac{m_j}{2} (W(|\vec{r}_i - \vec{r}_j|, h_i) + W(|\vec{r}_i - \vec{r}_j|, h_j))
\]

\[
[\nabla \rho]_i = \frac{\partial}{\partial \vec{r}_i} \sum_j^{N_n} m_j \overline{W}_{ij}(r_{ij})
\]

Dynamical equations:

\[
\frac{d\vec{r}_i}{dt} = \vec{v}_i \quad \frac{d\vec{v}_i}{dt} = \left[-\nabla \Phi\right]_i + \left[\frac{1}{\rho} \nabla P\right]_i + \vec{a}_{i, \text{visc}}
\]
Star Formation

SFR depends on local gas parameters available in SPH:

\[ \dot{\rho}_* = C_* \rho^n \max(\dot{u}, 0)^m \]

- \( n = 1.5, m = 0 \) \( \Rightarrow \) “density-dependent SF” (e.g. Katz 1992).
- \( n = 1.0, m > 0 \) \( \Rightarrow \) “shock-induced SF” (e.g. Barnes 2004).

Monte-Carlo method: chance of gas particle \( i \) becoming a stellar particle per time \( \Delta t \):

\[ P_i = C_* \rho_i^{n-1} \max(\dot{u}_i, 0)^m \Delta t \]

Record birthdate \( t_i^{\text{birth}} \) for each stellar particle formed in simulation.

Kennicutt (1998)
Luminosity Density


- initial stellar mass: $10^6 M_\odot$
- galactic IMF (Chabrier 2003)
- solar metal abundance
Luminosity Density


- initial stellar mass: $10^6 M_\odot$
- galactic IMF (Chabrier 2003)
- solar metal abundance

Correct to constant stellar mass (mass loss $\sim 50\%$ after $10^{10}$ yr).

Luminosity density in waveband $X$:

$$j_X(\vec{r}, t) = \int_{t'}^t dt' \rho_*(\vec{r}, t') / \Upsilon_X(t - t')$$

where

$$\rho_*(\vec{r}, t') \equiv \text{density of stars formed at time } t'$$

$$\Upsilon_X(\tau) \equiv \text{mass-to-light ratio of SSP with age } \tau$$
Radiative Transfer in $(2+1)$ D

The surface brightness $I_X$ along each line of sight is given by:

$$\frac{dI_X}{dz} = j_X - \rho\kappa_X I_X$$

Here $\kappa_X$ is the opacity, defined so that a gas surface density of $2 \times 10^7 \, M_\odot \, \text{kpc}^{-2}$ produces (c.f. Milky Way):

- $A_U = 1.531$
- $A_R = 0.748$
- $A_B = 1.324$
- $A_I = 0.482$
- $A_V = 1.000$
- $A_K = 0.112$

Bodies are first sorted by distance (far to near); the entire image can then be computed in one pass.

This approach does not include scattered light (much harder!).
Disk Galaxy Model

Bulge, Disk, Halo Components:

\[ \rho_b(r) \propto r^{-1}(r + a_b)^{-3} \]

\[ \rho_h(r) \propto r^{-1}(r + a_h)^{-2} \]

\[ \rho_d(R, z) \propto e^{-\alpha_d R} \text{sech}^2\left(\frac{z}{z_d}\right) \]

Distribution functions:

— bulge, halo: compute exact DF for spherical potential

\[
f_x(E) = \frac{1}{\sqrt{8\pi^2}} \frac{d}{dE} \int_E^0 \frac{d\Phi}{\sqrt{\Phi - E}} \frac{d\rho_x}{d\Phi}
\]

Eddington (1916)

— disk: use approx. DF consistent with moments of CBE

\[
f_d(R, z, v_R, v_\phi, v_z) \propto \rho_d(R, z) \mathcal{H}\left(\frac{v_R}{\sigma_R(R)}\right) \mathcal{H}\left(\frac{v_\phi - \bar{v}(R)}{\sigma_\phi(R)}\right) \mathcal{G}\left(\frac{v_z}{\sigma_z(R)}\right)
\]
Galaxy Model Parameters

Dimensionless quantities:
- mass: $m_b : m_d : m_h = 1 : 3 : 16$
- disk: $\alpha_d z_d = 0.15 \Rightarrow Q \approx 1.5$
- gas mass (% of $m_d$):
  12.5% ⇒ “Sb”, 25% ⇒ “Sc”

In simulation units ($G = 1$):
- bulge: $m_b = 0.0625$ $a_b = 0.02$
- disk: $m_d = 0.1875$ $\alpha_d = 12.0$ $z_d = 0.0125$
- halo: $m_h = 1.0000$ $a_h = 0.25$

Simulation parameters:
- smoothing: N-Body: $\varepsilon = 0.0075$; SPH: $h_i$ contains 40 bodies
- bodies: $N_g = 24576$ $N_b = 8182$ $N_d = 21504$ $N_h = 32768$
## Star Formation Parameters

<table>
<thead>
<tr>
<th></th>
<th>( n = 1.5 )</th>
<th>( n = 1 )</th>
<th>( n = 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>density (low)</td>
<td>( m = 0 )</td>
<td>( m = 0 )</td>
<td>( m = 0 )</td>
</tr>
<tr>
<td>shock (low)</td>
<td>( m = 0.5 )</td>
<td>( m = 0.5 )</td>
<td>( m = 0.5 )</td>
</tr>
<tr>
<td>shock (med.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>shock (high)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( C_* = 0.025 \) (Sb)

\( C_* = 0.018 \) (Sc)

\( C_* = 0.5 \)

\( C_* = 0.75 \)

\( C_* = 1.0 \)
Scaling to Physical Units

Simulations using dimensionless quantities \((r, m, t)\) can be rescaled to physical quantities \((R, M, T)\):

\[
R = L r \quad M = M m \quad T = T t
\]

Here \((L, M, T)\) have units of length, mass, and time, respectively.

For an N-Body simulation run with \(G = 1\), the only constraint is

\[
L^3 M^{-1} T^{-2} = G = 6.672 \times 10^{-8} \text{ cm}^3 \text{ gm}^{-1} \text{ s}^{-2}
\]

Thus a single model yields a 2-parameter family of solutions, all physically consistent.

An isothermal SPH simulation introduces an additional physical quantity, the sound speed \(c_s\). However, the exact value is not critical since ISM pressure is dynamically insignificant in galaxies.
Star Formation “Prehistory”

Finally, assign birthdates to bulge and disk particles, assuming:

— bulge formed 11 to 10 Gyr ago with constant SFR.
— disk began forming 10 Gyr ago with SFR \( \propto \exp(-\alpha_* t) \).
— disk SFR is (roughly) continuous at start of simulation.

Example: med. shock SF; scaling parameters:

\[
\begin{align*}
L &= 42.0 \text{kpc} \\
M &= 2.72 \times 10^{11} \text{M}_\odot \\
T &= 2.38 \times 10^8 \text{yr}
\end{align*}
\]
Star Formation “Prehistory”

Finally, assign birthdates to bulge and disk particles, assuming:
— bulge formed 11 to 10 Gyr ago with constant SFR.
— disk began forming 10 Gyr ago with SFR $\propto \exp(-\alpha_* t)$.
— disk SFR is (roughly) continuous at start of simulation.

Example: med. shock SF; scaling parameters:

\[
\begin{align*}
L &= 42.0 \text{kpc} \\
M &= 2.72 \times 10^{11} \text{M}_\odot \\
T &= 2.38 \times 10^8 \text{yr}
\end{align*}
\]

Draw birthdates $t_i^{\text{birth}}$ from age distributions for bulge and disk components.
Finally, assign birthdates to bulge and disk particles, assuming:

- bulge formed 11 to 10 Gyr ago with constant SFR.
- disk began forming 10 Gyr ago with SFR $\propto \exp(-\alpha_t \cdot t)$.
- disk SFR is (roughly) continuous at start of simulation.

Example: med. shock SF; scaling parameters:

$$L = 42.0 \text{ kpc}$$
$$M = 2.72 \times 10^{11} \text{ M}_\odot$$
$$T = 2.38 \times 10^8 \text{ yr}$$

Draw birthdates $t_i^{\text{birth}}$ from age distributions for bulge and disk components.
A Milky Way “Look-alike”

Sc model (25% gas); shock-driven SF (med.); above scaling gives:

\[ \alpha_d = 3.5 \text{kpc} \quad M_d = 5.1 \times 10^{10} \text{M}_\odot \quad V_c = 220 \text{km/s} \]
A Milky Way “Look-alike”

Sc model (25% gas); shock-driven SF (med.); above scaling gives:

\[ \alpha_d = 3.5 \text{kpc} \quad M_d = 5.1 \times 10^{10} \text{M}_\odot \quad V_c = 220 \text{km/s} \]

\[ M_{\text{bol}} = -23.0 \]
A Milky Way “Look-alike”

Sc model (25% gas); shock-driven SF (med.); above scaling gives:

$$\alpha_d = 3.5 \text{kpc} \quad M_d = 5.1 \times 10^{10} M_\odot \quad V_c = 220 \text{km/s}$$

$$M_{\text{bol}} = -23.0 \quad M_B = -21.6$$
A Milky Way “Look-alike”

Sc model (25% gas); shock-driven SF (med.); above scaling gives:

\[ \alpha_d = 3.5 \text{kpc} \quad M_d = 5.1 \times 10^{10} M_\odot \quad V_c = 220 \text{km/s} \]

\[ M_{\text{bol}} = -23.0 \]
\[ M_B = -21.6 \]
\[ M_B = -20.8, -19.5 \]
Effective Surface Brightness: Data vs. Models

Data: RC3 galaxies; high latitude, roughly face-on.

Models: shock-driven SF (med.); various scalings; extinction included.
Integrated Colors: Data vs. Models

Data: RC3 galaxies; high latitude; corrected to face-on.


SF options:
- shock (high)
- shock (med.)
- shock (low)
- density

Extinction included.
Integrated Colors: Data vs. Models

Data: RC3 galaxies; high latitude; corrected to face-on.


SF options:
- shock (high)
- shock (med.)
- shock (low)
- density

Extinction excluded.
Sc Models: Star Formation History

![Diagram showing the star formation rate history with different shock scenarios and density over time.](image-url)
Luminosity — Line Width Relation: Models vs. Data

**Data:** Tully & Pierce (2000) calibrator galaxies; face-on correction.

**Models:** shock-driven SF (med.); extinction included.

**Scaling:** $\Sigma = \text{const.}$

$M \rightarrow \alpha^4 M$

$L \rightarrow \alpha^2 L$

$T \rightarrow \alpha T$

$\alpha = \sqrt[4]{2}$
Luminosity — Line Width Relation: Models vs. Data

Data: Tully & Pierce (2000) calibrator galaxies; face-on correction.

Models: shock-driven SF (med.); extinction included.

Scaling: $\Sigma = \text{const.}$

$M \rightarrow \alpha^4 M$
$L \rightarrow \alpha^2 L$
$T \rightarrow \alpha T$
$\alpha = \sqrt[4]{2}$

Then: $V_c = \text{const.}$

$M \rightarrow \beta M$
$L \rightarrow \beta L$
$T \rightarrow \beta T$
$\beta = \sqrt[4]{3/4}$

Sc models

MW look-alike
Luminosity — Line Width Relation: Models vs. Data

Data: Tully & Pierce (2000) calibrator galaxies; face-on correction.

Models: shock-driven SF (med.); extinction included.

Scaling: \( \Sigma = \text{const.} \)

\[ \begin{align*}
M &\to \alpha^4 M \\
L &\to \alpha^2 L \\
T &\to \alpha T \\
\alpha &\equiv \sqrt{2}
\end{align*} \]

Then: \( V_c = \text{const.} \)

\[ \begin{align*}
M &\to \beta M \\
L &\to \beta L \\
T &\to \beta T \\
\beta &\equiv \sqrt{3/4}
\end{align*} \]
Isolated Galaxies: Summary

Surface brightness: models are consistent with data but a little brighter than average.

Integrated colors: models are consistent, but very blue colors are not attained unless extinction is set to zero.

Luminosity — line-width relation: scaled shock-driven (med.) models match slope and intercept.

Missing physics: (a) gas recycling; (b) scattered light.

Dust-to-gas ratio variable? Dust properties variable?
Merging Galaxies

Pick initial conditions, integrate forward in time, and compare to the observations.

Repeat until happy.

Scaling parameters are determined by match to data.
NGC 7252: Model Fit

Sc + Sc merger.

Scaling from fit:

\[ \mathcal{L} = 22.0 \, \text{kpc} \]
\[ \mathcal{M} = 9.96 \times 10^{10} \, \text{M}_\odot \]
\[ T = 1.54 \times 10^8 \, \text{yr} \]

1st passage about 6.2 \times 10^8 \, \text{yr} \, \text{ago.}
NGC 7252: Star Formation History

Sc models; shock-driven SF (low).
NGC 7252: Data vs. Model

$M_B = -21.22$
$U - B = 0.17$
$B - V = 0.66$
$V - R = 0.74$

$M_B = -20.68$
$U - B = 0.16$
$B - V = 0.60$
$V - R = 0.52$
NGC 4676: Model Fit

Sb + Sb merger.

Scaling from fit:

\[ L = 34.5 \text{kpc} \]
\[ M = 3.12 \times 10^{11} \text{M}_\odot \]
\[ T = 1.71 \times 10^8 \text{yr} \]

1\text{st passage about 1.7 \times 10^8 \text{yr ago.}}
NGC 4676: Animations

bol

BVR + dust
NGC 4676: Animations

bol

BVR + dust
NGC 4676: Animations
Thank You!
Star Formation: Implementation

SFR depends on local gas parameters available in SPH:

\[ \dot{\rho}_* = C_* \rho^n \max(\dot{u}, 0)^m \]

Monte-Carlo method: chance of gas particle \( i \) becoming a stellar particle per time \( \Delta t \):

\[ P_i = C_* \rho_i^{n-1} \max(\dot{u}_i, 0)^m \Delta t \]

Dissipation rate includes \( PdV \) work and artificial viscosity:

\[ \dot{u}_i = \sum_{j\neq i} N_n m_j \left( \frac{P_i}{\rho_i^2} + \frac{\Pi_{ij}}{2} \right) (\vec{v}_i - \vec{v}_j) \cdot \frac{\partial}{\partial \vec{r}_i} W_{ij}(r_{ij}) \]

Bulk + von Neuman-Richtmyer viscosity (Monaghan 1992):

\[ \Pi_{ij} = \begin{cases} \frac{-\alpha c_s \mu_{ij} + \beta \mu_{ij}^2}{(\rho_i + \rho_j)/2}, & \mu_{ij} < 0; \\ 0, & \text{otherwise} \end{cases} \]

\[ \mu_{ij} = \frac{(\vec{r}_i - \vec{r}_j) \cdot (\vec{v}_i - \vec{v}_j)}{r_{ij}^2 / h_{ij} + \eta^2 h_{ij}} \]