Andromeda in all colours

Sébastien Viaene and the HELGA team:

Why we like M31:

- Large galaxy (>10^{10}\,M_{\odot})
- Nearby (< 1 \, Mpc)
- Properties of ETG
- Properties of LTG
- Signs of a troubled past
Outline

- A vast dataset
- SED fitting and dust scaling relations
- Radiative Transfer Simulations
- Towards a complete model of M31
Herschel Exploitation of Local Galaxy Andromeda

HI + optical
Thilker et al. (2004)
Herschel Exploitation of Local Galaxy Andromeda

PACS 160 µm
Fritz et al. (2012)
HELGA: Dataset
Modelling the panchromatic SED of M31
HELGA: Herschel maps

> Cold dust emission
HELGA: Herschel maps

Cold dust emission
HELGA: FIR maps

MIPS 70 µm  
MIPS 24 µm  
WISE 22 µm

K. Gordon, T. Jarrett
HELGA: FIR maps

Warm dust emission

\[ \log(\lambda L_\lambda/L_\odot) \]

vs.

\[ \lambda (\mu m) \]
HELGA: FIR maps

Warm dust emission
HELGA: MIR maps

WISE 12 µm

IRAC 8 µm

IRAC 5.8 µm

WISE 3.3 µm

T. Jarret, P. Barmby
HELGA: MIR maps

Hot dust / PAH + stellar emission

\[ \log(\lambda L_\lambda / L_\odot) \]

\[ \lambda \text{ (\mu m)} \]
HELGA: MIR maps

Hot dust / PAH + stellar emission
HELGA: Optical/UV

Composite $gri$ (SDSS)

E. Tempel

GALEX NUV

D. Thilker
HELGA: Optical/UV

Stellar emission

\[
\log(\lambda L_\lambda / L_\odot)
\]

\[
\lambda (\mu m)
\]
HELGA: Optical/UV

Stellar emission (unattenuated)
Stellar emission (attenuated)

HELGA: Optical/UV
HELGA: Zooming in

Pixel-by-pixel SED fitting

- Masking foreground stars
- Convolution to SPIRE 500 $\mu$m beam
- Same pixel grid

Working resolution:
36” $\rightarrow$ 140 pc
Resulting Images

NUV

500 µm
Resulting Images

NUV

500 µm
Resulting Images

NUV

500 µm

22 436 independent pixels!
MAGPHYS: SED fitting

Multi-wavelength Analysis of Galaxy PHYSical properties
E. da Cunha et al. 2008

- Bayesian SED fits
- 75000 theoretical SEDs
- Construct Probability Density Functions (PDFs)
M31: Main Regions

Bulge pixel
$\chi^2 = 4.15$

Inner Disk pixel
$\chi^2 = 2.21$

Ring pixel
$\chi^2 = 2.44$

Outer Disk pixel
$\chi^2 = 0.78$
**M31: Parameter maps**

- $L_{\text{dust}}$
- $M_{\text{dust}}$
- $L_{\text{Tot PAH}}$
- $L_{\text{Tot}}$
- $T_{\text{ISM}}$
- $M_{*}$

Graphs showing different parameters with color scales and range indicators.
M31: Parameter maps
### M31: Local vs Global

<table>
<thead>
<tr>
<th>parameter</th>
<th>$N_{\text{pix}}$</th>
<th>Median $\sigma_{\text{rel}}$</th>
<th>Mean local</th>
<th>std. dev</th>
<th>Global $^{\pm \text{error}}$</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_\mu$</td>
<td>13462</td>
<td>0.10</td>
<td>0.85</td>
<td>0.08</td>
<td>$0.88^{+0.01}_{-0.02}$</td>
<td>--</td>
</tr>
<tr>
<td>sSFR</td>
<td>6608</td>
<td>0.18</td>
<td>3.45</td>
<td>0.02</td>
<td>$3.38 \pm 0.01$</td>
<td>$10^{-12}$yr$^{-1}$</td>
</tr>
<tr>
<td>$T^{\text{BC}}_W$</td>
<td>13462</td>
<td>0.21</td>
<td>43</td>
<td>7</td>
<td>$61^{+1}_{-9}$</td>
<td>$K$</td>
</tr>
<tr>
<td>$T^{\text{ISM}}_C$</td>
<td>13462</td>
<td>0.05</td>
<td>15.4</td>
<td>2.1</td>
<td>$16.2^{+0.3}_{-0.2}$</td>
<td>$K$</td>
</tr>
<tr>
<td>$\tau_V$</td>
<td>3753</td>
<td>0.14</td>
<td>0.62</td>
<td>0.68</td>
<td>$0.32 \pm 0.01$</td>
<td>--</td>
</tr>
<tr>
<td>$\tau^{\text{ISM}}_V$</td>
<td>13212</td>
<td>0.11</td>
<td>0.20</td>
<td>0.13</td>
<td>$0.16 \pm 0.01$</td>
<td>--</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>18053</td>
<td>--</td>
<td>1.26</td>
<td>--</td>
<td>$1.35$</td>
<td>--</td>
</tr>
</tbody>
</table>
## M31: Local vs Global

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<th>Total local</th>
<th>Global</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_*$</td>
<td>12853</td>
<td>0.17</td>
<td>4.76 ± 0.02</td>
<td>5.5 ± 0.01</td>
<td>$10^{10} M_\odot$</td>
</tr>
<tr>
<td>$M_{\text{dust}}$</td>
<td>10496</td>
<td>0.18</td>
<td>2.89 ± 0.06</td>
<td>2.7$^{+0.4}_{-0.1}$</td>
<td>$10^7 M_\odot$</td>
</tr>
<tr>
<td>$L_{\text{dust}}$</td>
<td>13462</td>
<td>0.06</td>
<td>4.542 ± 0.002</td>
<td>4.98$^{+0.6}_{-0.01}$</td>
<td>$10^9 L_\odot$</td>
</tr>
<tr>
<td>$SFR$</td>
<td>8673</td>
<td>0.16</td>
<td>0.1644 ± 0.0005</td>
<td>0.189$^{+0.002}_{-0.01}$</td>
<td>$M_\odot \text{yr}^{-1}$</td>
</tr>
<tr>
<td>$L_{\text{PAH}}^{\text{tot}}$</td>
<td>12563</td>
<td>0.12</td>
<td>0.8724 ± 0.0009</td>
<td>1.11$^{+0.03}_{-0.16}$</td>
<td>$10^9 L_\odot$</td>
</tr>
<tr>
<td>$L_{C}^{\text{tot}}$</td>
<td>10709</td>
<td>0.10</td>
<td>2.475 ± 0.002</td>
<td>2.55$^{+0.15}_{-0.01}$</td>
<td>$10^9 L_\odot$</td>
</tr>
</tbody>
</table>
HRS: Dust scaling relations

\[ \log(\mu_*) \left[ M_\odot / kpc^2 \right] \]

\[ \log(\theta) \left[ M_\odot / kpc^2 \right] \]

\[ \log\left( M_{\text{dust}} / M_* \right) \]

\[ \text{NUV-r} \]

Cortese et al. 2012
HRS: Dust scaling relations

\[ \log(\frac{M_{\text{dust}}}{M_*}) \]

\[ \log(\mu_*) \quad \left[ \frac{M_\odot}{kpc^2} \right] \]

NUV-r

M31

Bulge

Inner disk

Ring

Outer disk
HRS: Dust scaling relations
HRS: Dust scaling relations
M31: Dust scaling relations
M31: Dust scaling relations
M31: Dust heating sources
M31: Dust Scaling Relations

In Summary

- Panchromatic, sub-kpc SED modelling is now possible, BUT requires:
  - Special data treatment (masking, convolution,...)
  - Extended parameter space

- Resolved maps - 140 pc - of stellar and dust properties

- Sub-kpc regions follow galaxy-galaxy dust scaling relations; local nature of the underlying processes

The bulge of M31

NUV

Hα

8 μm

22 μm

250 μm

HI
The bulge of M31

Can radiative transfer simulations bring an answer?
Why 3D RT modeling?

- **Panchromatic (UV-mm) 3D RT models**
  - Self-consistent study of dust attenuation + dust emission
  - 3D asymmetric geometry of stars & dust
  - Non-local character of dust heating

What can we learn from 3D RT models?

- 3D spatial distribution, clumpiness of stars & dust
- Dust heating by old/young stars at $\lambda_{IR}$
- Non-locality of dust heating
- Grain composition/size distribution/properties

De Looze+2012a
The dust radiative transfer equation

\[ \frac{dI_\lambda(x, k)}{ds} = j_\lambda^*(x) - \kappa_\lambda^{\text{abs}} \rho(x) I_\lambda(x, k) - \kappa_\lambda^{\text{sca}} \rho(x) I_\lambda(x, k) \\
+ \kappa_\lambda^{\text{abs}} \rho(x) B_\lambda(T(x)) + \kappa_\lambda^{\text{sca}} \rho(x) \int I_\lambda(x, k') \Phi_\lambda(k, k') d\Omega' \]

Simultaneously solved

\[ \int_0^\infty \kappa_\lambda^{\text{abs}} I_\lambda(x) d\lambda = \int_0^\infty \kappa_\lambda^{\text{abs}} B_\lambda(T(x)) d\lambda \]

6D problem
- in space: propagation of photons across the domain
- in direction: scattering couples the intensity in all directions
- in wavelength: absorption/re-emission changes wavelength
SKIRT

Stellar Kinematics Including Radiative Transfer

- 3D continuum Monte Carlo
- C++ code in OOP-fashion in QT framework (Camps & Baes 2015)
- Parallel for shared and distributed memory systems
- Peeling-off technique, continuous absorption forced scattering, smart detectors, ...
- A variety of geometries (stellar, dust), different dust properties, grid structures, ...
- Smooth and clumpy models
- Mono-, oligo- and panchromatic mode
- LTE and NLTE

http://www.skirt.ugent.be
Forward Radiative Transfer

\[ j(R, z) = \frac{L_d}{4\pi h_{R,*}^2 h_{z,*}} \exp\left(-\frac{R}{h_{R,*}}\right) \exp\left(-\frac{|z|}{h_{z,*}}\right) \]

\[ \rho_d(R, z) = \frac{M_d}{4\pi h_{R,d}^2 h_{z,d}} \exp\left(-\frac{R}{h_{R,d}}\right) \exp\left(-\frac{|z|}{h_{z,d}}\right) \]

\[ j(R, z) = \frac{L_b}{q R_e^3} S_n\left(\frac{m}{R_e}\right) \]
Inverse Radiative Transfer

$$j(R, z) = \frac{L_d}{4\pi h_{R,*} h_{z,*}} \exp\left(-\frac{R}{h_{R,*}}\right) \exp\left(-\frac{|z|}{h_{z,*}}\right)$$

$$\rho_d(R, z) = \frac{M_d}{4\pi h_{R,d}^2 h_{z,d}} \exp\left(-\frac{R}{h_{R,d}}\right) \exp\left(-\frac{|z|}{h_{z,d}}\right)$$

$$j(R, z) = \frac{L_b}{q R_e^3} S \left(\frac{m}{R_e}\right)$$
Inverse RT: FitSKIRT

- Optimization using genetic algorithms
- C++, OOP, QT framework
- Stellar emission (~ U to K-band)
- Multiple geometries (mainly edge-on spirals)
- Shared/Distributed memory parallelization
- Handles MC noise/ degeneracies
Monochromatic fitting
Oligochromatic fitting
Advanced dust grids

Octree grids

Saftly+2013
Advanced dust grids

- Octree grids
- kd-tree grids

Saftly+2013
Advanced dust grids

- Octree grids
- kd-tree grids
- Voronoi grids

Saftly+2013

Camps+2013
Small scale structure

Circumbinary dust

ISM filaments

Star forming region

AGN torus
Simulating simulated galaxies
Simulating simulated galaxies

Saftly et al. 2014
Almost face-on ($i \approx 20^\circ$)
D $\approx 8.4$ Mpc
Huge dataset (FUV - 500 micron)
Complex geometry

Enables the construction of a high-resolution multi-wavelength RT model
3 main RT model components:
- Bulge: old stars (no dust)
- Thick disk: old stars
- Thin disk: dust ($h_{z,d} = 1/2 h_{z,\star}$) + (non)ionizing young stars
3D geometry

- Old stars: 2D geometry (x-y plane)
- 3D geometry (add z): $\exp(-|z|/h_z)$, $h_z = 450$ pc

IRAC 3.6 micron = Disc + Bulge
3D geometry

- Young stars: 2D geometry (x-y plane)
- 3D geometry (add z): \( \exp(-|z|/h_z) \), \( h_z = 100 \) pc

10-100 Myr
non-ionizing: FUV

< 10 Myr
ionizing: H\( \alpha \)+24 micron
3D geometry

Dust: 2D geometry (x-y plane)
- $A_{\text{FUV}}$ map: FUV-H to derive calibration coefficients
- 3D geometry (add z): $\exp(-|z|/h_z)$, $h_z = 225$ pc
Model results

Global SED
Model results

Spatially resolved maps
Model results

Colour maps
Model deviations up to $\approx 50\%$

- Spatial variation in ages/size of star clusters
  - E.g. younger stars in outer regions due to interaction with NGC 5195
- Relative grain abundance variations (PAH, VSG)
  - E.g. PAH destruction in hard RF, grain shattering due to shocks
- More diffuse dust component with large $h_{z,d}$

Vlahakis+2013

Calzetti+2005
Dust heating analysis

Graph showing the heating analysis of dust in different wavebands. The graph compares two curves:
- $F'(X, \text{old})$
- $F'(X, \text{young})$

The y-axis represents the percentage of heating, and the x-axis represents the waveband in microns ($\mu m$). The graph illustrates the heating distribution across different wavebands.
Dust heating analysis

Global TIR emission:
- 63% by young stars
- 37% by old stars
Galaxy with $M_\star \approx 10^{10} M_\odot$

$F_{\text{TIR, young}} = 100\%$ for $SFR \geq 2.0 M_\odot/yr$

$F_{\text{TIR, young}} = 50\%$ for $SFR = 0.5 M_\odot/yr$

Caution to link TIR to SF in non-starburst galaxies!
M31: RT model?

Working plan:

- Bulge-disk decomposition
M31: RT model?

Tempel et al. 2010
M31: RT model?

Working plan:

- Bulge-disk decomposition
- Prepare data products and first run
- Iteratively refine model
- Panchromatic SED fit -> main dust and SF properties.
M31: RT model?

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Working plan:

- Bulge-disk decomposition
- Prepare data products and first run
- Iteratively refine model
- Panchromatic SED fit -> main dust and SF properties.
- Full model & dust heating analysis
- ????
- Profit!