Dust Extinction, 3D Structure, and Stellar Properties from Resolved Stars in Nearby Galaxies

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October 4, 2022

with Claire Murray, Karl Gordon, Karin Sandstrom, and the ISM*@ST Group
The Interstellar Medium * Group at the Space Telescope Science Institute (STScI) is a collaboration between STScI research staff, associated external collaborators, and the students and postdocs with whom they work. We meet weekly, pool resources and expertise, and collaborate on research projects. We focus on interstellar, circumstellar, and circumgalactic media, mainly in nearby galaxies. But our interests are diverse and we often use stars and stellar populations in our analyses; hence the *. We hang out on the West 4th floor of the Rotunda.

Nearby Galaxies as Laboratories

The overall focus of the ISM*@ST group is the study of nearby galaxies (including the Milky Way) as laboratories for the physical processes of the ISM, star formation, stellar feedback, and galaxy evolution. We are broad in our approach: we use wavelengths from radio to ultraviolet, spectroscopy and imaging, Bayesian inference and deep learning, targeted observations and archival studies. The following are some areas of specific scientific focus:
Space Telescope Science Institute, Baltimore, Maryland, USA

- Established 1981
- About 800 people

- Performs (parts of) the science and mission operations for:
  - **Hubble** Space Telescope (HST, 1990)
  - James **Webb** Space Telescope (JWST, Dec. 25, 2021)
  - Nancy Grace **Roman** Space Telescope (2026)

- Performs scientific research

- Barbara A. Mikulski **Archive** for Space Telescopes (MAST) curates and disseminates data from 20+ missions
  
  `archive.stsci.edu`

- Handle proposals for HST, JWST
Motivation

Questions:

1. How are dust extinction / grain properties related to the Interstellar Medium (ISM)?

2. Can we probe the 3D ISM structure with individual sightlines, and learn where the dust-bearing gas is?

3. We want to apply a method systematically, to a variety of stellar populations and ISM environments?

4. Calibrate dust grain models via independent photometry-based extinction estimates (and avoid the uncertainty in dust opacity and emissivity).
Analysis:

We use multiband observations to model the photometric dust-extinguished SED of individual stars.

SMIDGE survey:
- 100 x 200 pc in SMC Southwest Bar
- About $10^6$ stars
- 9-band HST photometry
Scylla HST survey of the SMC & LMC

Scylla survey:
- 500 orbits in parallel with HST’s Ulysses (UV Legacy library of Young Stars as Essential Standards)
- 70 fields with massive stars, ~20 K stars each, ~1.4 x 10^6 stars
- Up to 7 band HST photometry
Small Magellanic Cloud SMIDGE Survey

SMC Spitzer Space Telescope 3.6, 8, and 24 μm SAGE-SMC survey (Gordon et al. 2011)

SMC N13

Las Campanas Observatory, Chile

© Ryan Trainer
SMC Red Clump Slope Measures the Extinction Curve

Observed Color-Magnitude Diagram (CMD)

Theoretical CMD

Colors & magnitudes encode info about:
- Individual stars’ T & L
- Amount and nature of the intervening dust,
- Ages and metallicities of the stars.

Yanchulova Merica-Jones et al., 2017

Dust, 3D Structure, & Stellar Properties from Resolved Stars
Red Clump Stars as Tracers of Dust Extinction

Theoretical synthetic CMD generated with MATCH/fake (Dolphin '02)

Yanchulova Merica-Jones et al., 2017
CMD Modeling to Fit 3D Structure & Dust Extinction Properties

CMD Fitting Results

- Dust:
  - $A(V)$, $\sigma(AV)$, $A(V)/NH$

- 3D Geometry:
  - Stellar distribution along LOS
  - Dust-stars offset (reddened fraction)

Extinction is measured in “magnitudes”, $A_\lambda$:

$$\frac{A_\lambda}{\text{mag}} = 2.5 \log \left( \frac{F_\lambda^0}{F_\lambda} \right)$$

Stellar flux (no extinction) $\rightarrow$ Observed stellar flux

Yanchulova Merica-Jones et al., 2017
SMC & LMC Extinction Curves

- We find an unexpected offset from UV spectroscopy (Gordon+ '03).
- We also tested this in the LMC and also find an offset in the LMC.
- The line-of-sight depth needs to be considered when using stars as a background to map dust.

Yanchulova Merica-Jones et al., 2017
What is Interstellar Dust?

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ISM@ST Research Group
24 Feb 2020

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@karlark2000
karlark@github

“Have Dust – Will Study”

P. Yanchulova Merica-Jones, STScI
Dust, 3D Structure, & Stellar Properties from Resolved Stars
What are the observed gas-phase abundances of the elements?

- **Composition**: small, solid grains: silicates, carbonates, and molecules containing C, O, Mg, Si, S, Fe.

- **Formation**:
  - “Stardust”: Formed in stellar atmospheres; blown into the ISM by stellar winds/outflows.
  - **Inside ISM**: growth by accretion & coagulation; depends on the availability of heavy elements.

- **Evolution**:
  - Depends on the formation–destruction balance
  - Dust-to-Gas & Dust-to-Metals ratios indicate a dependence on the fraction of heavy elements.

What materials may be present in the interstellar medium (ISM) to account for the observed extinction - scattering and absorption - of light?

**Interstellar grains**: 0.01 μm ≤ a ≤ 0.2 μm

Image by D. Brownlee and E. Jessberger

Interplanetary dust: porous chondrite

NASA Stardust Westphal+ 2014

Image by D. Brownlee and E. Jessberger

Interstellar grains: 0.01 μm ≤ a ≤ 0.2 μm

P. Yanchulova Merica-Jones, STScI Dust, 3D Structure, & Stellar Properties from Resolved Stars
The extinction at wavelength $\lambda$ characterizes the effects of absorption and scattering of starlight by dust.

Extinction is measured in “magnitudes”, $A_\lambda$:

$$\frac{A_\lambda}{mag} = 2.5 \log \left( \frac{F_\lambda^0}{F_\lambda} \right)$$

Stellar flux without extinction

Observed stellar flux

Changes in $R_V$: Dust Evolution

$R_V = \frac{A_V}{A_B - A_V}$

$\rightarrow$ Grain coagulation & accretion take place in the dense ISM, and increases $R_V$. 

What materials may be contributing to the observed extinction of light?

More small grains

$R_V = 3.1$

More large grains

$R_V = 4.0$

$R_V = 5.5$
The SMC extinction curve shows variations: lack of 2175Å bump & steep UV rise

- ISM properties appear to change at
  ~1/4 \( Z_{\text{solar}} \)  
  \( (Z_{\text{SMC}} \sim 1/5 \ Z_{\text{solar}}) \)

- Variations can be characterized by a mixture coefficient - \( f_A \).

\[
\frac{A_\lambda}{A_V} = f_A \left[ \frac{A_\lambda}{A_V} \right]_A + (1 - f_A) \left[ \frac{A_\lambda}{A_V} \right]_B
\]

Gordon et al., 2003
Spectral Energy Distribution Modeling with BEAST tool

Bottom: Full extinguished stellar spectrum with integrated SEDs for HST bandpasses at $\lambda_{\text{eff}}$. 

P. Yanchulova Merica-Jones, STScI

Dust, 3D Structure, & Stellar Properties from Resolved Stars
Spectral Energy Distribution Modeling with BEAST tool

- Photometric SED modeling tool, probabilistic Bayesian framework.
- Recovers intrinsic properties of individual stars and the dust along the sightline.
- Designed for large photometric surveys
- Accounts for dust extinction and observational uncertainties robustly
- Open source: github.com/BEAST-Fitting/

BEAST Physics Model Grid Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Resolution</th>
<th>Prior</th>
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</thead>
<tbody>
<tr>
<td>Stellar age, log(t) [Gyr]</td>
<td>6 – 10</td>
<td>0.2 dex</td>
<td>constant SFR</td>
</tr>
<tr>
<td>Stellar mass, log(M) [M☉]</td>
<td>-1.1 – 2.3</td>
<td>variable</td>
<td>Kroupa IMF</td>
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<tr>
<td>Stellar metallicity, Z/Z☉</td>
<td>0.193, 0.242, 0.306</td>
<td>0.2 mag</td>
<td>flat</td>
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<tr>
<td>Dust column, A_V [mag]</td>
<td>0.01 – 4.5</td>
<td>0.5</td>
<td>peaked at 2.74</td>
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<tr>
<td>Dust grain size, R_V</td>
<td>2.24 – 5.74</td>
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<td>flat</td>
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<tr>
<td>Dust mixture coefficient, f_d</td>
<td>0.0 – 1.0</td>
<td>7.0 kpc</td>
<td>flat</td>
</tr>
<tr>
<td>Distance [kpc]</td>
<td>55.0 – 69.0</td>
<td></td>
<td>flat</td>
</tr>
</tbody>
</table>

Bottom: Full extinguished stellar spectrum with integrated SEDs for HST bandpasses at λ_eff.
SED Modeling: Individual stellar and dust extinction properties

Yanchulova Merica-Jones in prep.
SMIDGE Results: $A(V)$, $R(V)$, $f_A$, $T_{\text{eff}}$, log($L$), log($g$), distance, age, mass, metallicity

The catalogs of stellar & dust parameters, for all stars, to be made publicly available.

Yanchulova Merica-Jones et al., in prep
Modeled CMD with reddened & unreddened stars

$T_{\text{eff}}$ comparison with literature

Yanchulova Merica-Jones et al., in prep
How are dust extinction properties related to the ISM environment?

**SMIDGE A(V) extinction map at 5.3''**

**APEX $^{12}$CO (2$\rightarrow$1) map of SMC SW Bar at 5.3'' (A. Bolatto)**

A(V): Dust extinction in the V-band

CO is the highest spatial resolution tracer we currently have of the SMC.

P. Yanchulova Merica-Jones, STScI

Dust, 3D Structure, & Stellar Properties from Resolved Stars
We see a positive $A(V)$ correlation with low & high CO intensity:
→ Two independent measurements are correlated.
→ CO can be used as a dust column density tracer.

$\text{SMIDGE } A(V) \text{ extinction map } + ^{12}\text{CO} \ (2−1) \text{ map contours (APEX/ALMA, A. Bolatto)}$

CO is the highest spatial resolution ISM tracer we have for the SMC - an excellent tracer of the dense ISM.
In Three Dimensions: Dust column vs Distance (Scylla survey)

Preliminary, C. Murray
SMC Targeted UV Spectroscopy Dust Extinction Curves

HST STIS UV extinction curve idea for sightlines with a high probability of a 2175 Å bump.

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<td>16.77</td>
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<td>1.0</td>
</tr>
</tbody>
</table>

PAHs: polycyclic aromatic hydrocarbons
Carriers of 2175 Å bump?

N(HI)  

$^{12}\text{CO} (2-1)$

$R_v(V) = 3.1; f_A$ variable
- $f_A = 0.0; A_V = 2.36$; G00 SMC Star
- $f_A = 0.5; A_V = 2.9$; G0 F9
- $f_A = 1.0; A_V = 3.1$; MW F9

PAH fraction
Conclusions

✦ We can generate high-quality **catalogs & maps** of **dust & stellar** properties of millions of stars in nearby galaxies, and make them publicly available.

  - A(V), R(V), \( f_A \), \( T_{\text{eff}} \), \( \log(L) \), \( \log(g) \), distance, age, mass, metallicity

✦ We can model (almost) all observed stellar populations and probe all ISM sightlines.

✦ We can test dust properties correlation with ISM tracers:

  First impressions: Strongest correlation is between A(V) and CO as an ISM tracer. Weaker between R(V) & \( f_A \) and CO, or with other dust tracers.

Future work:

✦ A wealth of existing and upcoming surveys can be fit with the BEAST

✦ With code development, we can make robust quantitative statements about the ensemble properties of stars and dust.

✦ Target specific sightlines or ISM clouds to investigate correlations.

Scylla (MCs), SMIDGE (SMC), PHAT (M31), HTTP (LMC), PHATTER (M33), PHANGS (NGs), PHAST (M31+), JWST+

- petiay.github.io
- github.com/BEAST-Fitting

P. Yanchulova Merica-Jones, STScI Dust, 3D Structure, & Stellar Properties from Resolved Stars
SMC Dust Extinction and 3D Geometry

- We used resolved stars to constrain SMC’s 3D structure & dust extinction
- In the Magellanic Clouds when using stars as a background to map the dust, one needs to take into account BOTH the dust extinction and the 3D structure of the galaxy.
- A CMD-based extinction result can estimate dust mass independently of dust grain models

**Limitations:** We used only $\sim 10^4$ red clump stars and measured only average dust properties.

**Motivation to build onto this work:**
- Systematically derive dust and stellar properties for a large sample ($\sim 10^6$ stars), for all stellar populations.
- Produce high-quality catalogs, make publicly available.
Red Clump Stars as Tracers of Dust Extinction

Theoretical synthetic CMD generated with MATCH/fake (Dolphin '02)

Brighter

Magnitude

Fainter

Color

Red Clump

Red Giant Branch

Main Sequence

Without dust (Simulated)

With dust (Observed)

N_{STARS} (without dust) = N_{STARS} (with dust)

Yanchulova Merica-Jones et al., 2017

Theoretical synthetic CMD generated with MATCH/fake (Dolphin '02)
• We find an unexpected offset from UV spectroscopy (Gordon+ ’03).
• We also tested this in the LMC and also find an offset in the LMC
• The line-of-sight depth needs to be considered when using stars as a background to map dust
Simulations of the history of the Magellanic Clouds show interactions impacting the shape of the galaxies (Nidever+ '08, Besla+ '07, '12, '16, Y. Choi+ '18).

We found a simpler explanation: SMC’s depth along the line of sight is significantly larger than its width along the plane of the sky (4 - 5 times).

Studies conclude large line-of-sight depth of the SMC (Florsch+ ’81, Subramanian x 2 ’09,’12,’17, Nidever+’13, Jacyszyn-D+’16,’17, Scowcroft+’16).

Simulations of the history of the Magellanic Clouds show interactions impacting the shape of the galaxies (Nidever+ ’08, Besla+ ’07, ’12, ’16, Y. Choi+ ’18).

Similarly, the LMC has a depth along the line of sight (~ 5 kpc) which is a significant fraction of its distance of ~50 kpc (Monson+ ’12).

Extinction Curve from the Reddened Red Clump
Yanchulova Merica-Jones et al, 2017
The depth of the galaxy needs to be considered. With a red clump toy model we simulate galactic depth and dust extinction:

• The stars behind the dust are farther away than expected. This makes them appear fainter (mag ↑).
• Gray dust: large faction of large grains causing a (big) change in magnitude (mag↑) with little/no change in color.

→ Both of these lead to a steeper reddening vector slope.

→ The distance effect is perceived as the perfect gray extinction.

→ The depth of the galaxy needs to be considered.
The offset from UV spectroscopy (Gordon+ '03) can be explained by depth along the line of sight.

There is no need to invoke “gray” dust.
How are dust extinction properties related to the ISM environment? \( R_V, f_A \) maps

**\( R(V) \):** Average dust grain size; Describes extinction curve slope.

\( f_A \): Dust mixture coefficient; Specifies fraction of MW-type dust extinction.
Do we see a correlation between stellar properties and the ISM?

$\log(T_{\text{eff}})$

$\log(\text{Age})$

$M/M_\text{solar}$

Dust mass surface density ($\Sigma_{\text{Md}}$) contours, from IR dust emission

Gordon+, '14

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Dust, 3D Structure, & Stellar Properties from Resolved Stars
Observing Stars and Dust at Low Metallicity

Why is dust at low-metallicity important?

• Most star formation in the Universe took place at low metallicity.

• To understand the SFH of the Universe, we need to understand dust at low Z.

• Dust extinction properties appear to change at low metallicity.

\[
Z_{\odot} \approx 0.014 \quad (1.4 \%) \\
Z_{\text{LMC}} \approx 0.5 \, Z_{\odot} \quad (0.7 \%) \\
Z_{\text{SMC}} \approx 0.2 \, Z_{\odot} \quad (0.3 \%)
\]

Dufour '84, Asplund+ '09, Russell & Dopita '92, Rolleston+'99, etc.

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Dust, 3D Structure, & Stellar Properties from Resolved Stars