X-raying the Interstellar Medium

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LIneA
August 8, 2019
Stars probe the ISM in 3D

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Observables: amount of material, its size distribution, its velocity, its chemical composition, the magnetic field . . .
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*We can map all of these in three dimensions*
Outline

Introduction

3D Maps of Dust Density

Dust Properties in 3D

New Surveys
Outline

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3D Maps of Dust Density

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New Surveys
What is dust?
What is dust?

“holes in the heavens” (Herschel)
Dust is Important

- Astrophysically
- Observationally
Dust is Astrophysically Important
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- enables star formation
  - cooling
  - shielding
  - catalyzing
- tiny mass (1% of gas)
- 30% of light from the Milky Way
Dust is Astrophysically Important

- enables star formation
  - cooling
  - shielding
  - catalyzing
- tiny mass (1% of gas)
- 30% of light from the Milky Way
- planets
Dust is Observationally Important

Schlegel, Finkbeiner, Davis (1998)
Dust is Observationally Important

Schlegel, Finkbeiner, Davis (1998)

- dust **extinguishes** UV/optical/NIR light
- dust emits IR, millimeter, microwave light
- observationally hard to avoid
Dust is observationally important

- Dust extinguishes UV/optical/NIR light
- Dust emits IR, millimeter, microwave light
- Observationally hard to avoid
- 10,000 citations
Current Dust Maps are only 2D

- Current maps give only the total dust column.
- Distance is also important!
Current Dust Maps are only 2D
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New Surveys
How to make a 3D map of dust

1. Large survey of stars
2. Precise photometry
3. Distance and reddening estimate for each star
4. Invert to get 3D map
Star-based 3D dust maps

Generally, tomographic analysis
  - infer 3D structure from noisy measurements of integrated density
  - CT scan
Star-based 3D dust maps

- \( \sim 10^9 \) stars needed for good spatial resolution
- Distances and amounts of dust are very uncertain
- Fit parameters are all coupled
  - more distant stars must be behind more dust than nearby ones
  - dust clouds are spatially correlated
- naively several billion parameter model \( \rightarrow \) impossible
Star-based dust maps

- cannot just average (e.g., with a Wiener filter): distances are uncertain
- Most 3D dust maps ignore the distance uncertainty!
Star-based dust maps

➢ cannot just average (e.g., with a Wiener filter): distances are uncertain
➢ Most 3D dust maps ignore the distance uncertainty!

However...
➢ the problem can be factorized (Schlafly+14, Green, Schlafly+14)
➢ fit the amount of dust and the distance to each star, tracking full covariance
➢ pixelize sky and fit each line-of-sight independently
➢ iterate to introduce correlations
Star-based dust maps

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However...

- the problem can be factorized (Schlafly+14, Green, Schlafly+14)
- fit the amount of dust and the distance to each star, tracking full covariance
- pixelize sky and fit each line-of-sight independently
- iterate to introduce correlations
- impossible problem $\rightarrow$ very expensive problem (2.5 million CPU hours) (Green, Schlafly+14, 15, 18)
Does it work?
(movies)
Results

- unprecedented map of Milky Way dust (Green, Schlafly+14, 15, 18)
- best distances to molecular clouds (Zucker, Schlafly+19)
- dust property variations in 3D (Schlafly+16, 17)
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New Surveys
The Extinction Curve

Fitzpatrick (1999) extinction curve

Diagnostic of dust grain size distribution
Variation in the extinction curve

Cardelli, Clayton, & Mathis (1989)
Variation in the extinction curve

Cardelli, Clayton, & Mathis (1989)
Entirely empirical curve, presumably determined by:
- grain size distribution
- grain composition
- grain processing
Dust evolution

Zhukovska & Henning (2014)
The Pair Method

- Simple method: compare spectra of reddened and unreddened stars
- Dates back to Trumpler, Johnson, ...
- Huge number of stars probing Milky Way available today
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Fitzpatrick & Massa (2007), 328 stars
The Pair Method

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APOGEE & PS1 & 2MASS & WISE, 37000 stars (Schlafly+16)
How does the extinction curve vary spatially?
How does the extinction curve vary spatially?

Dominant variations on large scales, *not* small scale variations in dense molecular clouds.
But what about 3D?
Dust Properties in 3D

2D → 3D

- 3D dust map made with 10\,9\,20,000 stars with good \( R(V) \) measurements
- How to infer 3D \( R(V) \) map?

\[
R'(V) = \int D_{0} \rho(l, b, s) D(l, b, s) \int D_{0} \rho(l, b, s)
\]

- Linear problem, especially easy to solve if \( R(V) \) is smooth in 3D.
2D → 3D

- 3D dust map made with $10^9$ stars
- 20,000 stars with good $R(V)$ measurements
- How to infer 3D $R(V)$ map?
2D → 3D

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  \[ R(V) = \frac{\int_0^D ds \rho(l,b,s)R_3D(l,b,s)}{\int_0^D ds \rho(l,b,s)} \]
- Linear problem, especially easy to solve if $R(V)$ is smooth in 3D.
2D → 3D

Clear imprint of 3D structure onto projected 2D $R(V)$ map
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2D $\rightarrow$ 3D

Clear imprint of 3D structure onto projected 2D $R(V)$ map
Galactic $R(V)$ Map

Kiloparsec scale structures, possible Galactic gradient?
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New Surveys
We can see a *lot* of stars in the Milky Way
We can see a *lot* of stars in the Milky Way

Precise photometry of billions of overlapping stars is challenging!
Modeling images: traditional approach

- Single object: easy
  - position, brightness, few shape parameters
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- Many objects: hard, due to *blending*
- Must simultaneously solve for fluxes and positions of all the sources
- Can be $10^5$ sources per image!
New Surveys

Modeling images: traditional approach

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- Many objects: hard, due to blending
- Must simultaneously solve for fluxes and positions of all the sources
- Can be $10^5$ sources per image!
- Typical approaches either ignore the problem, iterate, or try to cleverly segment the image.
Crowded Field Modeling: Our approach

This is very nearly a linear problem

\[ f(x, y) = \sum_{i} f_i P(x - x_i, y - y_i) + B(x, y) \]

- fluxes \( f \) are linear
- sky background \( B \) can be parameterized with a linear model
- positions \( x_i, y_i \) can have good initial estimates, can be linearized

- sparse: each source occupies only \( \sim 10^{-4} \) of the image
- Large scale linear algebra packages can solve problems with hundreds of thousands of parameters, e.g., via conjugate gradient method
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A New Crowded Field Photometry Pipeline

This approach works!

- crowdsourc (Schlafly+2018)
- Applied to DECam Plane Survey and WISE Survey (Schlafly+18, 19)
- $\sim 4$ billion detected sources!
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New Surveys

Applying crowdsourcing to real images
Applying crowdsourcing to real images

- Asteroid characterization
- Nearby, ultra-cool stars (Backyard Worlds)
- High-redshift quasars (e.g., $z = 7.5$, Bañados+2018)
- Galaxy surveys: $\sim 500$ million galaxies over $0 < z < 2$ (Schlafly+19)
- Galactic structure: $\sim$ billion stars (Schlafly+19)
The unWISE Catalog (Schlafly+19)

Galactic Anticenter W1
The unWISE Catalog (Schlafly+19)
The unWISE Catalog (Schlafly+19)

Galactic Anticenter W1 crowdsourcing
The unWISE Catalog (Schlafly+19)

Galactic Anticenter W1 crowdsourcing model
3× more stars and galaxies... what can we do with this?
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- Correlation with Planck lensing, ISW maps (Ferraro, Krolewski, White, Schlafly)
- MaDCoWS2 galaxy cluster search, sensitive to $1 < z < 2$ (Gonzalez)
- Nearby stars using six-month WISE coadds (Meisner, Schlafly)
The DECam Plane Survey
Source Density
Source Density

20 billion detections of 2 billion objects
Science

- New star clusters (Torrealba+2019)
- Predicted microlensing events (McGill+2018)
- High resolution 3D star & dust maps (Green, Zucker, Schlafly)
Conclusion

- Large, precise surveys x-ray the ISM, revealing
  - 3D density of dust at high resolution
  - Dust grain size distribution
  - Velocity field, magnetic field also accessible

- Bright future
  - DECam, WISE surveys of billions of stars
  - Transformative data from Gaia & SDSS-V
  - Numerous other forthcoming spectroscopic and photometric surveys
How to make a 3D map of dust (Green, Schlafly+2014)

- $10^9$ PS1 stars
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How to make a 3D map of dust (Green, Schlafly+2014)

Monoceros (99.1, -10.73) (618 stars)

► $10^9$ PS1 stars

► Reddening and distance inference

► Line of sight fit
How to make a 3D map of dust (Green, Schlafly+2014)

- $10^9$ PS1 stars
- Reddening and distance inference
- Line of sight fit
- 2.5M CPU hours
- Lots of related work!
  - Sale+2014, Sale+2015, Sale+2017
  - Marshall+2006
  - Lallement+2014
For next-generation surveys, most fields are crowded

- Next generation surveys have more objects, meaning more overlapping objects
- Two-thirds of galaxies will be blended in LSST (Melchior+2018)
  - $\sim 15\%$ of blends will be unrecognized (Dawson+2016)
- The easy case: assume all objects are point sources
  - surveys with low spatial resolution (WISE, Kepler, TESS)
  - microlensing surveys
Results (Schlafly+19)

- 3× more stars and galaxies
Results (Schlafly+19)

The image shows a sky map with coordinates $l$ and $b$, representing longitude and latitude, respectively. The map is a representation of the distribution of stars and galaxies, with the intensity color-coded. The map is labeled 'W1' and 'AllWISE', indicating different datasets or images overlaid. The map covers a range of $l$ from $150^\circ$ to $-150^\circ$ and $b$ from $80^\circ$ to $-80^\circ$.
Results (Schlafly+19)

![Graph showing the distribution of stars and galaxies in the Interstellar Medium with Enhanced Photometric Uniformity.](image)
Results (Schlafly+19)

- 3× more stars and galaxies

- > 500 million galaxies, 0 < z < 2 (largest galaxy catalog in world?)
Results (Schlafly+19)

The figure shows a histogram of the number of galaxies versus redshift for different data sets:

- **AllWISE**: Light blue bars
- **unWISE**: Orange bars
- **SDSS Spectroscopy**: Green line

The x-axis represents redshift ranging from 0.0 to 4.0, and the y-axis represents the number of galaxies. The data includes a catalog of over 500 million galaxies with redshifts in the range 0 < z < 2, described as the largest galaxy catalog in the world. The histogram also highlights enhanced photometric uniformity.
Results (Schlafly+19)

- $3 \times$ more stars and galaxies

- $> 500$ million galaxies, $0 < z < 2$ (largest galaxy catalog in world?)

- enhanced photometric uniformity
Results (Schlafly+19)
Future Directions

- Transdimensional searches (Daylan+2016)
- Beyond maximum likelihood point estimate
- Machine learning to tell stars from galaxies
- Multi-epoch, multi-band analysis
Extinction and Emission are Linked

Planck team models dust emission with a modified blackbody:

\[ I(\nu) = \tau_\nu B_\nu(T)(\nu/\nu_0)^\beta \]
Extinction and Emission are Linked

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\[ I(\nu) = \tau_{\nu} B_{\nu}(T)(\nu/\nu_0)^\beta \]

Strong correlation between dust SED and \( R(V) \)
Zasowski+2015
Does $R(V)$ vary systematically with $E(B - V)$?

No correlation between $R(V)$ and $E(B - V)$, but $E(B - V)$ is dust column density rather than volume density tracer. APOGEE Reddening Survey in APOGEE-2 to resolve this issue.
\( R(V) \) with \( E(B - V) \)
$R(V)$ with $E(B - V)$
$R(V)$ with $E(B - V)$

![Graph showing $R(V)$ vs $E(B - V)$ for Ori A]
$R(V)$ with $E(B - V)$
$R(V)$ with $E(B - V)$
$R(V)$ with $E(B - V)$
Distance Catalog

Schlafly+2014

Eddie Schlafly (LBL)  X-raying the Interstellar Medium  August 8, 2019
The Orion Dust Ring
Slice dust into foreground, Orion, and background
The Orion Dust Ring
Slice dust into foreground, Orion, and background
2D Comparison: Aquila South

Problems hard to avoid in "reddening" maps based on extinction.

Future reddening maps will be star-based.
Problems hard to avoid in “reddening” maps based on extinction.
Future reddening maps will be star-based.
How variable is the extinction curve?

Somewhat smaller dispersion than literature (0.27), many fewer high $R(V)$ sight lines (9.5% in FM07)
3D $R(V)$ Map Accuracy

![Graph showing the comparison between 3D model $E(g - r)$ and measured $E(g - r)$, as well as 3D model $R(V)$ and measured $R(V)$, with a diagonal line indicating perfect accuracy.]
Extinction and Emission are Linked

Planck (2014) $\beta$ map
Extinction and Emission are Linked

Large and small scale features in $\beta$ closely linked to variations in $R(V)$. 