Deciphering Local, Multiphase HI with 21-SPONGE and Artificial Intelligence

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What sets a galaxy's efficiency to form molecular gas?

Initial conditions for GMC formation: atomic reservoir

Schruba et al. 2011
What are the properties ($T_s$, $N$(HI), etc...) of the HI phases?

\[ T_s \sim \frac{1}{\tau} \]
Measuring $T_s$: need HI emission and absorption.

\[
T_{b\text{on}} = T_{b\text{kg}} e^{-\tau} + T_s (1 - e^{-\tau})
\]
\[
T_{b\text{off}} = T_s (1 - e^{-\tau})
\]
How much mass exists in each HI phase of the ISM?

*CNM, WNM, and unstable fractions depend on input physics*

(e.g. MacLow et al. 2005, Audit & Hennebelle 2005, Hill et al. 2012)

Audit & Hennebelle 2005
Comparing observations with theory is essential, but difficult!
Needed:

1. Deeper, statistically significant observational constraints

2. Comparison strategy

3. Synthetic observations of simulations
Needed:

1. Deeper, statistically significant observational constraints
21-SPONGE
21-cm Spectral line Observations of Neutral Gas with the (E)VLA

• 57 sources (37 complete): S>3 Jy, |b|>10

• High-sensitivity HI absorption: $\sigma_\tau \sim 7 \times 10^{-4}$

• New time-averaged bandpass calibration dramatically improves RMS and efficiency

• Filler project! 571 VLA hours / 3 years

• High detection rate: 36/37
21-SPONGE

21-cm Spectral line Observations of Neutral Gas with the (E)VLA

VLA (Begum+10): 10 hrs

exp(-r)

Velocity (km/s)

3C286

public.nrao.edu; naic.edu
21-SPONGE

21-cm Spectral line Observations of Neutral Gas with the (E)VLA

EVLA (Begum+10): 10 hrs

$\exp(-t)$

Velocity (km/s)

3C286
21-SPONGE

21-cm Spectral line Observations of Neutral Gas with the (E)VLA

EVLA (21-SPONGE): 3 hrs

3C286

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2. Comparison strategy

AUTONOMOUS GAUSSIAN DECOMPOSITION (AGD)

Lindner et al. 2015, AJ, 149, 138
AUTONOMOUS GAUSSIAN DECOMPOSITION (AGD)

- Automatic, efficient decomposition of 1D spectral data into Gaussian functions via derivative spectroscopy
- Initial guesses are chosen without human interaction

Lindner et al. 2015, AJ, 149, 138
3. Synthetic Observations

- 3D hydrodynamical Galactic ISM simulation (Kim et al., 2013, 2014)
- Includes:
  - Supernova feedback
  - Self gravity
  - ISM heating and cooling
  - 2pc spatial resolution
- $10^4$ synthetic HI spectra

Simulations

Physical quantities

\[ \tau_i, \sigma_i^v, \Delta \nu_i, \]

\[ \downarrow \]

Synthetic spectra

\[ \downarrow \]

AGD()

\[ \downarrow \]

Gaussian components

\[ \tau_i, \sigma_i^v, \Delta \nu_i, \]

Observations

Observed spectra

\[ \downarrow \]

AGD()

\[ \downarrow \]

Gaussian components

\[ \tau_i, \sigma_i^v, \Delta \nu_i, \]
Do Gaussians Correspond to Clouds?
Matching Gaussians to Clouds in Simulations

- **Density**
  - **LOS distance**
  - **Density** $n$ in $g \text{ cm}^{-3}$

- **Optical Depth**
  - **Velocity**
  - **Optical Depth** $\tau$

The diagrams illustrate the comparison of simulated density and optical depth profiles with Gaussian fits at different LOS distances and velocities.
Matching Gaussians to Clouds in Simulations

First statistically-robust quantification of cloud-component correspondence!

Unique cloud recovery fraction:

| $|b| = 0 - 20^\circ$ | $69\%$ |
|----------------------|--------|
| $|b| = 20 - 50^\circ$ | $83\%$ |
| $|b| = 50 - 90^\circ$ | $92\%$ |
Comparing AGD Absorption Parameters

- **BLUE CONTOURS:**
  $10^4$ AGD-processed synthetic HI absorption lines (Kim et al. 2014)

- **BLACK:**
  37 AGD-processed 21-SPONGE VLA HI absorption lines (Murray et al. 2015)

"blue ridge" 1, 2 and 3 $\sigma$ contours

"red cloud"
Comparing AGD Absorption Parameters

- **BLUE CONTOURS:** $10^4$ AGD-processed synthetic HI absorption lines (Kim et al. 2014)
- **BLACK:** 37 AGD-processed 21-SPONGE VLA HI absorption lines (Murray et al. 2015)
Comparing CNM and WNM Absorbing LOS

Such absorption lines, with no CNM, are RARE!
How much CNM is there?
How much CNM is there?

“CNM” = $T_s < 200$ K

Simulation data:
Kim et al. 2014

Simulation data:
Kim et al. 2014
Simulated Mass Fractions by Temperature

[Graph showing the fraction of gas as a function of temperature (K), with two distinct regions labeled CNM and WNM. The graph is labeled with the data source: Simulation data: Kim et al. 2014.]
Simulated Mass Fractions by Temperature

Ratio of “true” to “observed” = observational bias correction!

Simulation data: Kim et al. 2014
Observed Mass Fractions by Temperature

Simulation data: Kim et al. 2014

Work in progress!
Observed Mass Fractions by Temperature

Work in progress!

Simulation data: Kim et al. 2014
Search for HI gas at even higher \( Ts \)...

Search for HI gas at even higher $T_s$...

$\langle T_s \rangle = 7200^{+1800}_{-1200}$ K

Bootstrap MC simulation, $10^5$ trials

Search for HI gas at even higher $T_s$…

Stacked emission

Stacked absorption

$\langle T_s \rangle = 7200^{+1800}_{-1200}$ K

Resonant Ly$\alpha$ scattering (Wouthuysen-Field effect)?


Bootstrap MC simulation, $10^5$ trials
Summary

• **21-SPONGE** will constrain the uncertain mass distribution of HI as a function of $T_s$, as the largest high-sensitivity HI absorption survey:
  • Sensitive to unstable and warm gas mass
  • Evidence for $T_s \sim 7000$ K gas, weaker at high latitude

• **Autonomous Gaussian Decomposition (AGD)** enables fast and consistent comparisons between observations and simulations:
  • Confirms correspondence between HI clouds and Gaussian spectral features
  • CNM fraction agrees very well with predicted average $T_s$ trends
  • CNM detection rate is higher in observations than simulations

• **Need more HI emission/absorption observations and synthetic observations of simulations to improve statistics!**