THE SPIN TEMPERATURES OF THE GALAXY & HIGH-z DAMPED LYMAN-α SYSTEMS

Nissim Kanekar
National Centre for Radio Astrophysics, Pune

Jason X. Prochaska
Alain Smette
Frank Briggs
Wendy Lane
Emmanuel Momjian

Sara Ellison
Jayaram Chengalur
Nirupam Roy
Robert Braun
Max Pettini

Image: B. Premkumar
OUTLINE

• The HI-21cm spin temperature.

• Galactic HI-21cm absorption studies: An N(HI) threshold for CNM formation?

• Damped Lyman-α absorbers (DLAs).

• HI-21cm absorption studies of a large sample of DLAs.

• A metallicity – spin temperature anti-correlation in DLAs.
THE HI-21CM SPIN TEMPERATURE

- For HI-21cm absorption studies of compact sources:

\[ N(\text{HI}) = 1.8 \times 10^{18} \times \int T_s \times \tau_{21} \, dV. \]

\[ T_s \equiv \text{“Spin” temperature: } [n_2/n_1] \propto e^{-h\nu/kT_s} \]

- N(\text{HI}) from Lyman-\(\alpha\) absorption or HI-21cm emission.

(e.g. Wakker et al. 2011, ApJ)

- Single cloud \(\Rightarrow\) Infer \(T_s\) by measuring \(\int \tau_{21} \, dV\).

- Multi-phase medium: Infer \(<T_s>\), column-density-weighted harmonic mean of \(T_s\) in the warm and cold phases.

\[ T_C \sim 100 \text{ K} \quad n_W \sim n_C \sim 0.5 \quad \Rightarrow \quad <T_s> \sim 200 \text{ K}. \]

\[ T_W \sim 8000 \text{ K} \quad \Rightarrow \quad n_W \sim 0.9, \quad n_C \sim 0.1 \quad \Rightarrow \quad <T_s> \sim 1000 \text{ K}. \]

- \(<T_s>\)(Galaxy) \(\sim 100 – 300 \text{ K}; \quad <T_s>\)(SMC) \(>\sim 450 \text{ K}.\)

**AN N(HI) THRESHOLD FOR CNM FORMATION?**

(NK et al. 2011, ApJL)

- Interferometric Galactic HI-21cm absorption survey with the ATCA, the GMRT and the WSRT (10 – 24 hours per target).

- Bandpass calibration with frequency-switching every 5m. Two sources observed with WSRT+GMRT to test quality.

- 34 compact quasars, mostly at Galactic latitude $>> 10^\circ$. Optical depth sensitivity $\sim 0.0003 – 0.001$ per 0.3 – 0.5 km/s $N$(HI) $\sim 10^{20}$ cm$^{-2} – 10^{22}$ cm$^{-2}$.

- HI-21cm absorption detected against 33 of 34 quasars. $N$(HI) measured from the LAB HI-21cm emission survey.

$N(\text{HI}) = 2 \times 10^{20} \text{ cm}^{-2}$

$T_s = 600 \text{ K}$

(NK et al. 2011, ApJL)
**An N(HI) Threshold for CNM Formation?**

(NK et al. 2011, ApJL)

- Low spin temperatures, \( \sim 250 \text{ K} \), for \( N(\text{HI}) \geq 2 \times 10^{20} \text{ cm}^{-2} \).
- Sightlines with low \( N(\text{HI}) \) have systematically higher \( T_s \).
  \( \Rightarrow \) Sharp drop in CNM fraction at \( N(\text{HI}) < 2 \times 10^{20} \text{ cm}^{-2} \).
- Inefficient self-shielding against soft X-ray / UV photons?
- Possibly *four* phase “transitions” in the ISM:
  
  (1) \( N(\text{HI}) \sim 10^{17} \text{ cm}^{-2} \) : \( \text{HII} \rightarrow \text{HI} \).
  
  (2) \( N(\text{HI}) \sim 2 \times 10^{20} \text{ cm}^{-2} \) : Warm \( \text{HI} \rightarrow \) Warm + Cold\( \text{HI} \).
  
  (3) \( N(\text{HI}) \sim 5 \times 10^{20} \text{ cm}^{-2} \) : \( \text{HI} \rightarrow \text{HI} + \text{H}_2 \). (Savage et al. 1977, ApJ)
  
  (4) \( N(\text{HI}) \sim 10^{22} \text{ cm}^{-2} \) : \( \text{HI} \rightarrow \text{H}_2 \).
  
DAMPED LYMAN-α SYSTEMS (DLAs)

(e.g. Wolfe et al. 2005, ARA&A)

- High HI column density, \( N(\text{HI}) \geq 2 \times 10^{20} \text{ cm}^{-2} \).
- Absorption-selected \( \Rightarrow \) No luminosity bias.
- “Normal” gas-rich galaxies!
- Low metallicities, \([Z/H] < -1\).
- Optical imaging difficult due to the background QSO.

What galaxies are DLAs at different redshifts? Typical mass, kinematics, physical conditions?

- HI-21cm absorption directly probes the HI in DLAs!

Note: HI-21cm emission studies near-impossible at high \( z \).
**HI-21cm Absorption Studies of DLAs**

- Until 1998, 3 detections at $z > 0.7$, 4 at $z < 0.7$, few limits. (e.g. Wolfe & Davies 1979, AJ; Wolfe et al. 1985, ApJL)

- Reasons: Poor frequency coverage, low sensitivity, RFI!

Giant Metrewave Radio Telescope
- 30 dishes, 45-m diameter.
- $z \sim 0 – 0.6, 1.1 – 1.5, 2.9 – 3.6.$

Green Bank Telescope
- 110-m dish, $z \sim 0 – 3.6.$
HI-21cm Absorption Searches in DLAs

- VLT, Gemini & WHT optical survey of radio-loud QSOs to find DLAs for follow-up HI-21cm spectroscopy. (Ellison et al. 2008, MNRAS)
- 45 DLAs & 90 MgII absorbers observed with the GBT and the GMRT; roughly one-third wiped out by RFI!
- ~25 new HI-21cm absorption detections, at 1.1 < z < 3.4.
- 39 spin temperature estimates in DLAs, 27 at z > 1.
- 20 of 22 DLAs at z > 2 have high T_s; typically > 1000 K.
$z \sim 2.19$

$z \sim 2.29$

$z \sim 2.35$

$z \sim 3.39$
**Spin Temperatures in DLAs**

- 39 $T_s$ estimates in DLAs, 22 at $z > 2$.
- 20/22 DLAs at $z > 2$ have high $T_s$.
- High $T_s$ values ⇒ High WNM fraction in high-$z$ DLAs.
- 4.2$\sigma$ evidence for redshift evolution in DLA spin temperatures.
- $T_s$ in DLAs and the Galaxy different at 6$\sigma$ significance.

(NK et al. 2013, MNRAS)
High $T_s$ due to low DLA metallicities and a paucity of cooling routes $\Rightarrow$ Anti-correlation between $T_s$ and $[Z/H]$!

- Higher metallicity, $Z \sim 1$ $\Rightarrow$ More CNM $\Rightarrow$ Low $T_s$
- Lower metallicity, $Z < 0.1$ $\Rightarrow$ Less CNM $\Rightarrow$ High $T_s$.


(NK & Chengalur 2001, A&A)
Non-parametric Kendall–τ test ⇒ 4σ anti-correlation!

HIGH SPIN TEMPERATURES IN DLAs?

- Gas distribution in a 2-phase medium depends on the metallicity and pressure.
  Higher metallicity, pressure ⇒ More CNM ⇒ Low $T_s$
  Lower metallicity, pressure ⇒ Less CNM ⇒ High $T_s$

- High-z DLAs have low metallicities: median $[Z/H] \sim -1.5$.
  ⇒ The HI in most high-z DLAs is mainly in the WNM.
  (NK et al. 2013, MNRAS)

- Dwarfs ⇒ Low pressure, star formation, metallicity
  ⇒ More WNM ⇒ High spin temperature.
  ⇒ Most high-z DLAs are likely to be small galaxies.

- But... High-z DLAs have large velocity spreads, $\sim 90$ km/s.
SUMMARY

- Spin temperature measurements in the Galaxy:
  \( T_s \sim 240 \text{ K} \) for \( N(\text{H}I) \geq 2 \times 10^{20} \text{ cm}^{-2} \).
  \( T_s > 1000 \text{ K} \) for \( N(\text{H}I) < 2 \times 10^{20} \text{ cm}^{-2} \).

- A column density threshold for CNM formation? A third phase transition in the ISM?

- A physical difference between DLAs and sub-DLAs?

- 39 \( T_s \) estimates in DLAs, with 22 at \( z > 2 \). Most high-\( z \) DLAs have high spin temperatures (\( >\sim 1000 \text{ K} \)).

- 4\( \sigma \) anti-correlation between \( T_s \) and metallicity [Z/H]
  \( \Rightarrow \) High \( T_s \) in DLAs is due to a high WNM fraction.
  \( \Rightarrow \) Most of the HI in high-\( z \) DLAs is in the WNM.
HI-21CM ABSORPTION STUDIES: A BRIEF HISTORY

• 1973: HI-21cm absorption at $z \sim 0.692$ towards 3C286.

• $z_{21\text{cm}}$ vs. $z_{\text{UV}}$ at $z \sim 0.524 \Rightarrow$ Fundamental constant evolution!
  (Wolfe et al. 1976, PRL)

• 1979-1985: Three absorbers at $z \sim 1.776, 1.944, 2.040 \Rightarrow$
  First evidence for high spin temperatures in high-$z$ DLAs.
  (e.g. Wolfe & Davies 1979, AJ; Wolfe et al. 1985, ApJL)

• 1983: HI-21cm absorption survey targeting MgII absorbers.

• 1997: Tentative detection at $z \sim 3.4$; not confirmed later.

• Until 1998, 3 detections at $z > 0.7$, 4 at $z < 0.7$, few limits.

• Reasons: Poor frequency coverage, low sensitivity, RFI!
HI-21cm Absorption at Low Redshifts

- Low-$z$ DLA surveys require large amounts of HST time.

- HI-21cm absorption only detectable in DLAs ⇒ Find DLAs via HI-21cm surveys in strong MgII absorbers.

- 38 MgII absorbers at $0.6 < z < 1.7$; $W_{\text{MgII, FeII}} > 0.5$ Å.
  Either 21cm detections or strong limits on the HI-21cm optical depth ($\tau_{21} < 0.013$).

- 9 (16) detections of 21cm absorption, at $1.07 < z < 1.67$
  ⇒ 21cm detection rate in DLAs $\sim 69^{+31}_{-23}$%.

- Detection rate at $z \sim 1$ comparable to that at low $z$
  ⇒ Significant amounts of cold HI present by $z \sim 1$.
HI-21cm ABSORPTION STUDIES: MOTIVATION

- HI-21cm emission is very difficult to detect ($z_{\text{MAX}} \sim 0.25$). Even for the SKA, ~360 hours to detect $M^*_\text{HI}$ at $z \sim 2$!
- HI-21cm absorption *directly* probes conditions in the neutral atomic ISM in high-$z$ galaxies.
- DLAs towards *extended* radio sources $\Rightarrow$ Transverse size & kinematics.
- DLAs towards *compact* radio-loud QSOs $\Rightarrow$ DLA spin temperatures $\Rightarrow$ Evolution of the temperature of the neutral ISM with redshift.
- Strong MgII absorbers at $z < 1.7$ $\Rightarrow$ Finding low-$z$ DLAs.
- $z_{21\text{cm}}$ versus $z_{\text{UV}}, z_{\text{OH}}$ $\Rightarrow$ Fundamental constant evolution.
COS spectroscopy of the $z \sim 1.371$ system toward UM305.

$N_{\text{HI}} = (6 \pm 1) \times 10^{21} \text{ cm}^{-2}$

$\Rightarrow T_s = (1000 \pm 150) \text{ K.}$

(Ellison et al. 2012, MNRAS)
MAPPING HIGH-\(z\) HI-21CM ABSORPTION

- Can measure the size and velocity field of DLAs lying towards extended radio sources (e.g. radio galaxies).
- Long-baseline interferometers for high spatial resolution!
- Best target: the \(z \sim 0.437\) DLA towards 3C196.

(Briggs et al. 2001, A&A)

(Ridgway & Stockton 1997, AJ)
MAPPING HI-21CM ABSORPTION AT $z \sim 0.437$
Integrated optical depth

Velocity field

Mapping HI-21cm Absorption at $z \sim 0.437$
VLBA Imaging ⇒ DLA covering factors

30 QSOs observed at 327, 610 or 1420 MHz.

0336-017, $z \sim 3.062$, $f \sim 0.68$

0201+113, $z \sim 3.387$, $f \sim 0.76$
39 QSOs with covering factor measurements.

Covering factor vs. redshift

Transverse size vs. redshift

⇒ Similar covering factors at all redshifts, \( 0.4 < f < 1 \)

⇒ Covering factor effects not significant.

Consistent picture if high-$z$ DLAs are typically small galaxies, with low SFR, metallicity and CNM fraction.