Tracing Baryons in the Warm Hot Intergalactic Medium using Broad Lyman-α Absorbers

Mid-Term 2

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Thesis Phase I : Recap

Recap

- **The missing baryon problem**
- BLAs : Way to probe WHIM
- Absorber towards PG 0003+158
- BLA survey : 28 BLA candidates

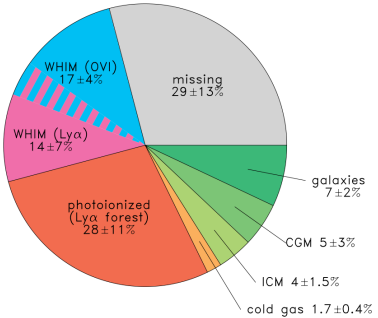

Figure 1: Baryon budget at $z \sim 0$.
Shull et al. (2012)

Recap

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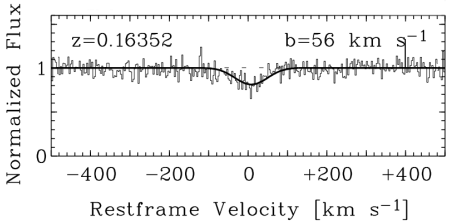

Figure 2: A BLA towards the LOS of quasar H 1821+643. Philipp Richter (2005)

Recap

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- BLA survey : 28 BLA candidates

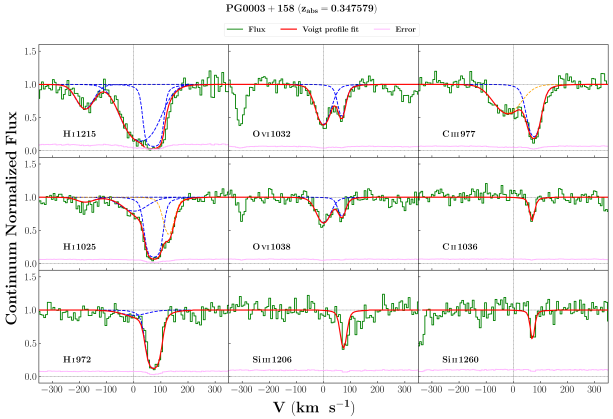

Figure 3: System plot of the absorber system towards PG 0003+158. Velocity is taken zero at z = 0.347579

Recap

- The missing baryon problem
- BLAs : Way to probe WHIM
- Absorber towards PG 0003+158
- **BLA survey : 28 BLA candidates**

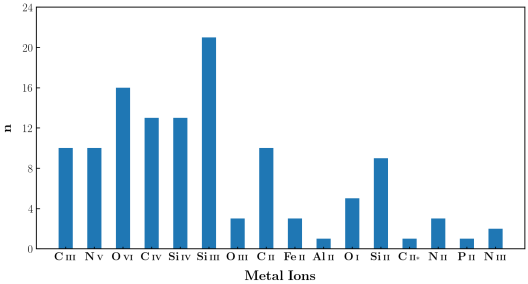

Figure 4: Distribution of metal ions in all 28 candidate BLAs

The BLA Survey

Survey so far...

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- Voigt profile fitting : 16 (O VI) + **6**

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- Voigt profile fitting : 16 (O VI) + **6**
- Ionisation Modelling : **16 (O VI)**

Insights

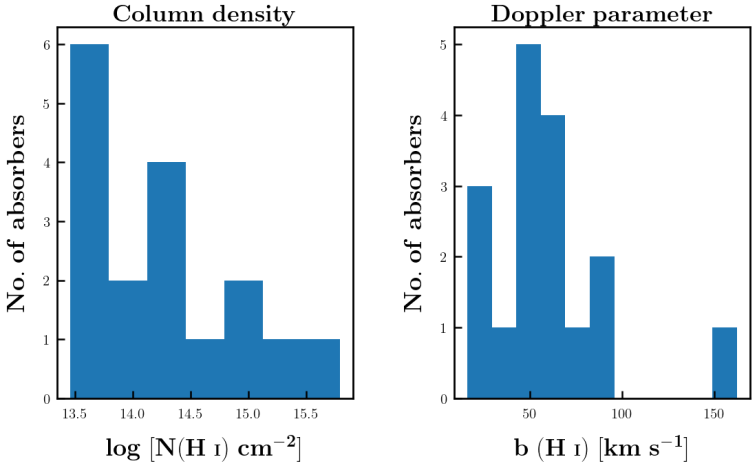

Figure 5: Distribution of H I column densities and Doppler parameters.

Insights

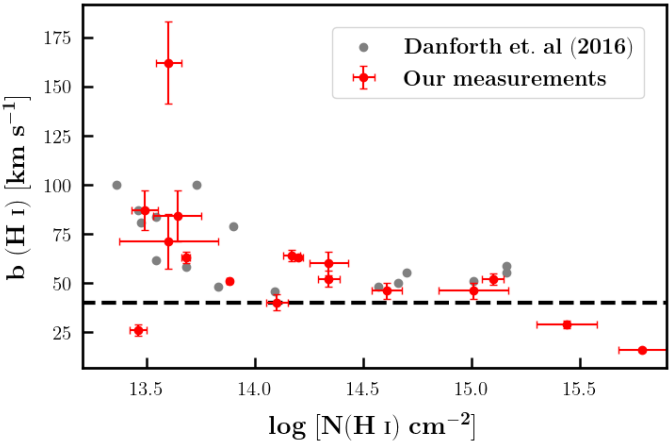

Figure 6: H I column density vs. Doppler parameter

Insights

$$b^2 = b_{th}^2 + b_{nt}^2$$

$$b_{th}^2 = \frac{2kT}{m}$$

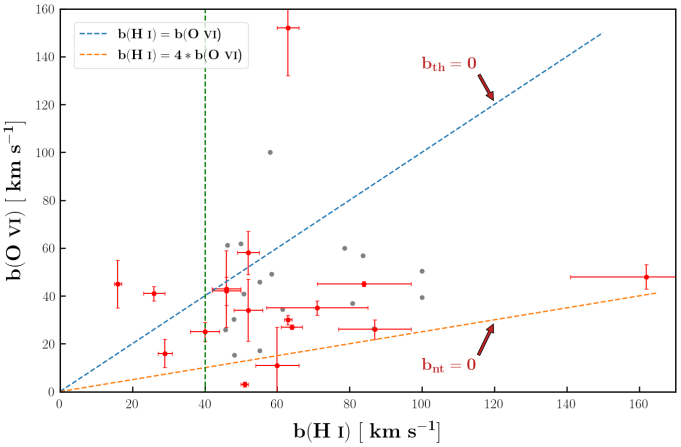

Figure 7: b(O VI) vs. b(H I). Grey filled circles are measurements from Danforth et. al (2016).

Insights

$$T = \frac{8m}{15k}\left(b^2_{\mathrm{H\,I}} - b^2_{\mathrm{O\,VI}}\right)$$

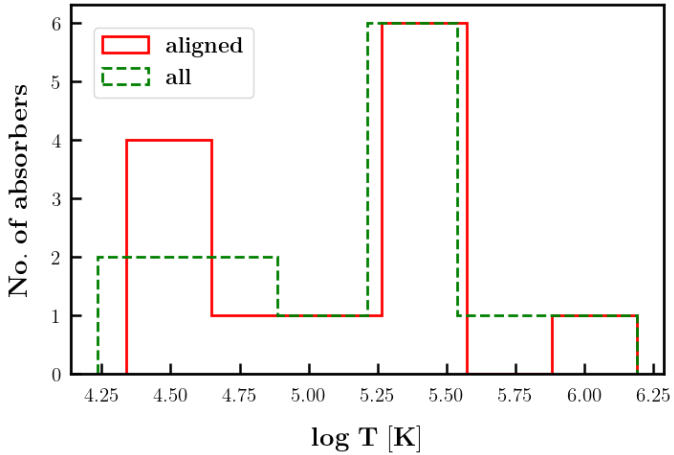

Figure 8: Distribution of temperature calculated from Doppler parameters of H I and O VI lines.

Ionisation Modelling

Method

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- Grid of PI CLOUDY models : Density and Metallicity

Ref. : Acharya and Khaire (2021)

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- log $(Z/Z\odot)$: -3 to 2 in steps of 0.05

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Method

- Grid of PI CLOUDY models : Density and Metallicity
- log (n_H/cm^{-3}) : -5 to 1 in steps of 0.02
- log $(Z/Z\odot)$: -3 to 2 in steps of 0.05
- Solution : Model that best predicts the observed column densities

Ref. : Acharya and Khaire (2021)

Results

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- 16 O VI absorbers

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- 26 components

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- 26 components
- Origin of O VI

Solutions

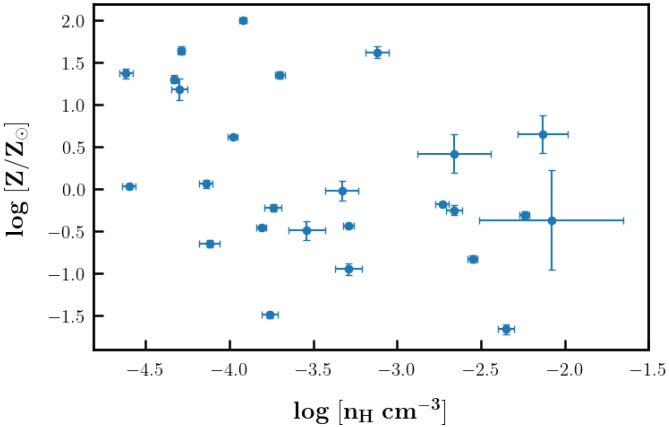

Figure 9: Ionisation modelling solutions (n_H, Z) for all 26 components.

+ve correlation

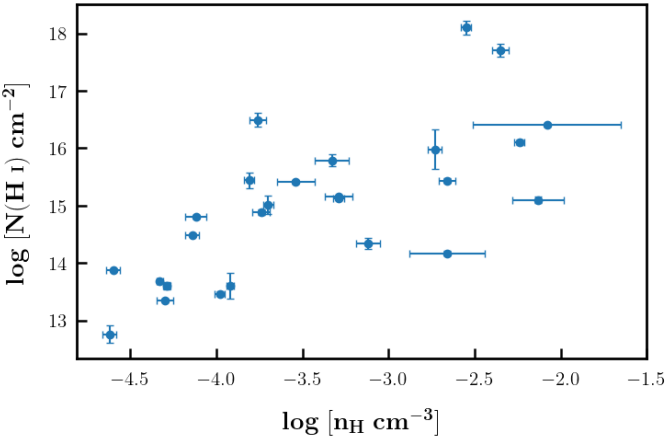

Figure 10: Variation of N(H I) with n_H

O VI cases

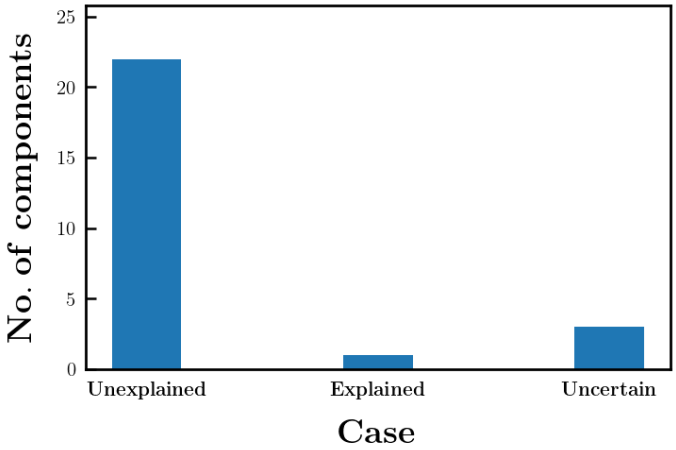

Figure 11: O VI column density predictions.

Ex : Unexplained

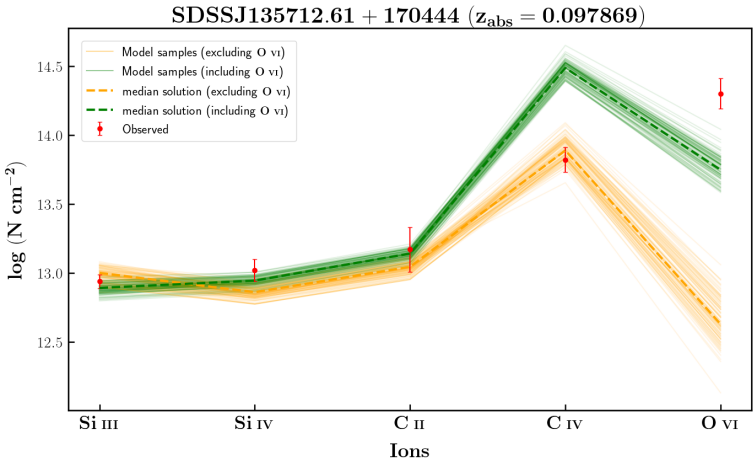

Figure 12: N(H I)=16.49 cm^{-2}

Ex : Explained

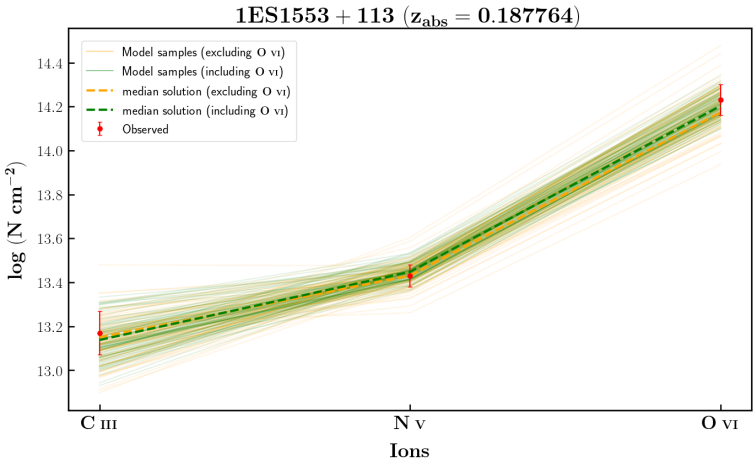

Figure 13: N(H I)=12.76 cm^{-2}

Ex : Uncertain

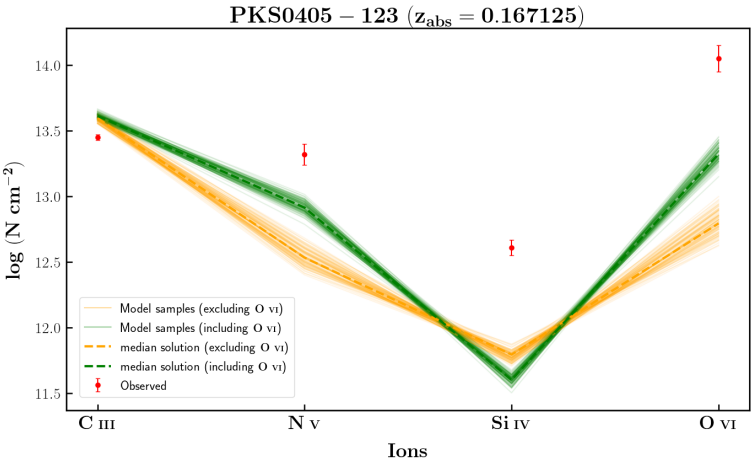

Figure 14: N(H I)=13.46 cm^{-2}

Towards *the end*

Ongoing and Future Work

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- Voigt profile fitting : 6

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Ongoing and Future Work

- Voigt profile fitting : 6
- Ionisation modelling : 12
- Exploring the survey results
- *Finally*, calculating $\Omega_b(BLA)$

Outcomes

- Poster presentation at ASI-2024 meet titled "Tracing Baryons in WHIM using BLAs"

Tracing Baryons in the Warm-Hot Intergalactic Medium using Broad Lyman-α Absorbers

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Introduction

- More than 90% of baryons reside in IGM and CGM at $z \sim 0$.
- Out of these 90% baryons, more than 30% are still unaccounted for in observations (Shull et al. 2012).
- Structure formation simulations show that these missing baryons reside in Warm Hot phase of Intergalactic Medium (WHIM).
- WHIM : Difficult to observe - low density and high temperature
- Broad Lyman-α Absorbers (BLAs) are expected to be large reservoirs of baryons.
- We probe WHIM using BLAs and estimate their contribution in the total baryonic energy density of universe.

Objectives

- Comprehensive survey of BLAs
- To estimate contribution of BLAs to the total cosmic baryon inventory

Observations

- HST/COS data in FUV channel : 1130-1790 Å
- High S/N > 15 per resolution element
- v_{FWHM} ~ 17,000 (17 km s^{-1})

Studying an Absorber system : Methods

- Voigt profile fitting - VPFIT
  - Gives positions, widths and column densities of ions
- Ionization Modeling – CLOUDY
  - To infer ionization state of the absorber cloud
  - To determine physical conditions prevailing in the absorber system
- Galaxy neighborhood
  - To deduce origins of the absorber system

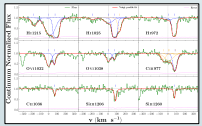

Fig. 1 : System plot of an absorber at $z \sim 0.347$ towards the line of sight of quasar PG0003+158 ($z = 0$ at $z = 0.347579$)

Absorber towards PG 0003+158 : Results

- **Voigt profile analysis (fig. 1)**
  - 3 component system at $z \sim 0.347$
  - Component I : Lyα and Lyβ at $v \sim -180$ km s^{-1}
  - Component II : Lyα - Lyδ, O VI at $v = 0$ km s^{-1}; T~$10^{5.4}$ K **(BLA)**
  - Component III : H I 1215-914, O VI, C II, C III, Si II, Si III at $v \sim 70$ km s^{-1}
- **Ionization Modelling**
  - All ions in component III can be explained using photoionization models **except O VI. (fig. 2)**
  - So, **O VI** could be tracing **collisionally ionized gas phase.**

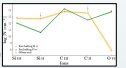

Fig. 2 : Observed and modelled column densities of ions in component III

- **Galaxy Environment**
  - VIMOS : 5 galaxies identified in the field - $L \leq 0.07 L^*$ **(fig. 3)**
  - Absorber residing in galaxy under -dense region, could be tracing a large scale filamentary structure in the cosmic web or CGM of galaxy farther than 0.07 L^*

Fig. 3 : Galaxy environment around the absorber LOS color-coded with velocity separation from the absorber

BLA Survey : Ongoing work

- Presented results are part of our ongoing large survey of BLAs
- Identified 28 more BLA candidates for the survey
- Methods described currently are being carried out on these 28 BLA candidates.
- Results from these 28 systems will be used to estimate contribution of BLAs in the total cosmic baryon inventory.

Conclusion

- Addressed uncertainties in Baryon census in WHIM using BLAs
- Studied an interesting absorber system, possibly tracing a large scale filamentary structure or a CGM of sub- L^* galaxy.
- Results are awaited from the whole survey of additional 28 absorbers.

References

- *Shull J. M., Smith B. D., Danforth C. W., 2012, ApJ, 759, 23*
- *Danforth C. W., et al., 2016, ApJ, 817, 111*
- *Acharya A., Khaire V., 2021, MNRAS, 509, 5559*
- *Khaire V., Srianand R., 2019, MNRAS, 484, 4174*

Summary

- Voigt profile fitting : 22 absorbers - 231 Voigt profiles
- Ionisation modelling : 16 absorbers - 26 components
- O VI couldn't be explained with photoionization models
- BLA survey towards completion

References

Acharya A., Khaire V., 2021, MNRAS, 509, 5559

Danforth C. W., et al., 2016, ApJ, 817, 111

Lehner N., Savage B. D., Richter P., Sembach K. R., Tripp T. M., Wakker B. P., 2007, ApJ, 658, 680

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Savage B. D., Kim T. S., Wakker B. P., Keeney B., Shull J. M., Stocke J. T., Green J. C., 2014, ApJS, 212, 8

So much universe, and so little time...

Appendix

- Outlier b(O VI)

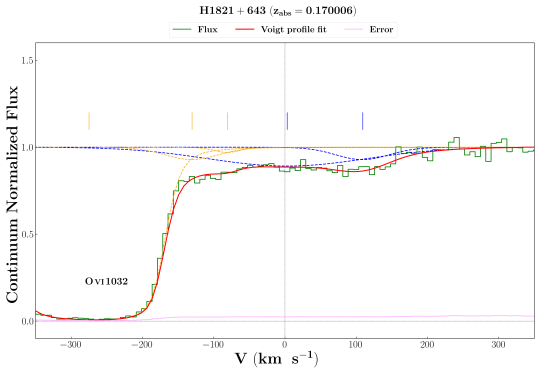

Figure 15: Voigt profile fit of O VI 1032 line in absorber system towards H1821+643 at $z_{abs} = 0.170006$