

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

Thesis Phase I

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The Missing Baryon Problem

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- ▶ $\sim 50\%$ baryons were missing
- ▶ Recent studies shows deficit of 20-30%

Ref. : Fukugita et al. (1998)
Shull et al. (2012)

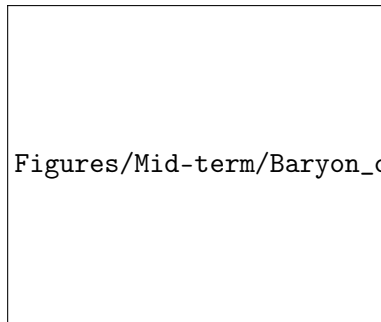


Figure 1: Baryon budget at $z \sim 0$.
Shull et al. (2012)

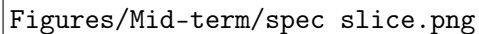
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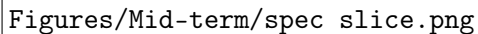


Figures/Mid-term/spec slice.png

Figure 2: Slice of spectrum of quasar HE0153-4520 ($z_{em} = 0.4510$).
Danforth et al. (2016)

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 - O VI-VIII, Ne IX-X, N VII, etc.



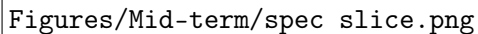
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Figures/Mid-term/BLA-individual.png

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Figure 3: A BLA towards the LOS of quasar H 1821+643 ($z_{em} = 0.297$)
Philipp Richter (2005)

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Figures/Mid-term/BLA.png

Figure 4: A BLA blended with other Ly α absorption lines towards the LOS of quasar PG1116+215 ($z_{em} = 0.176$). Philipp Richter (2020)

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Savage et al. (2014)

Data

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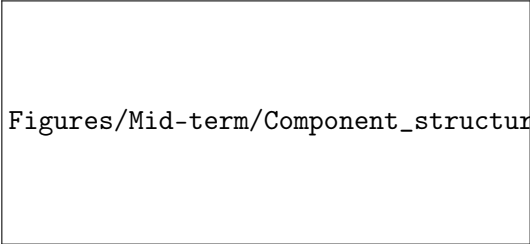
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- ▶ $R \sim 17,000 \approx 17 \text{ km s}^{-1}$

Phase I

Absorber system towards PG0003+158

Absorber system

- ▶ Quasar at $z_{em} = 0.45089$
- ▶ $z_{abs} \sim 0.347$
- ▶ 3 component system



Figures/Mid-term/Component_structure2.png

Voigt profile fitting

Figures/Mid-term/PG0003+158- $z=0.347579$ -sys-plot.png

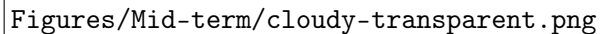
Figure 5: System plot of the absorber system. Velocity is taken zero at $z = 0.347579$

Voigt profile fitting

- ▶ H I : 3 components
- ▶ O VI : 2 components
- ▶ C II, C III, Si II, Si III : 1 component

Figures/Mid-term/param.png

CLOUDY



Figures/Mid-term/cloudy-transparent.png

Figure 6: Schematic diagram of CLOUDY simulations.

Ionization Modelling

- ▶ Component I : -
- ▶ Component II : Hybrid - Collisional + Photo-ionization
- ▶ Component III : Photo-ionization (PI)

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- ▶ Grid of CLOUDY models : Density and Metallicity

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- ▶ $\log (n_{\text{H}}/\text{cm}^{-3})$: -5 to 1 in steps of 0.02
- ▶ $\log (Z/Z_{\odot})$: -3 to 2 in steps of 0.05
- ▶ Solution : Model that best matches the observed column densities

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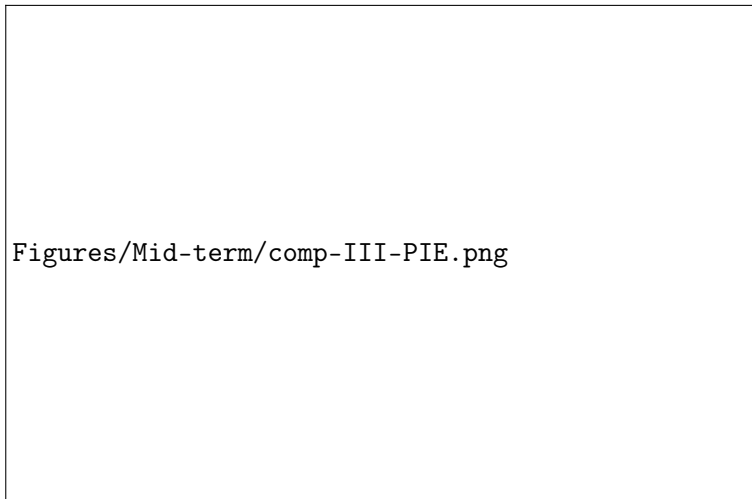
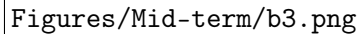


Figure 7: Modelled and observed column densities for the component III based on photoionization modelling

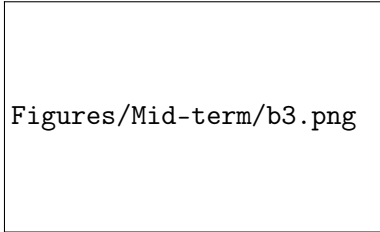
Component II : Hybrid

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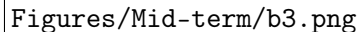
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► $T = 10^{5.29^{+0.07}_{-0.08}} \text{ K}$

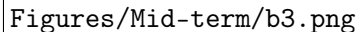
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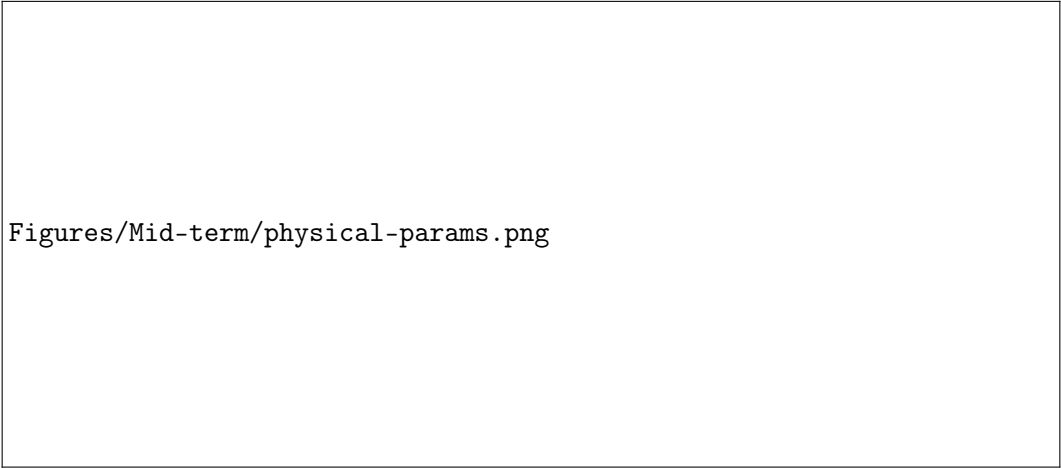
- ▶ $T = 10^{5.29^{+0.07}_{-0.08}} \text{ K}$
- ▶ Constant temperature CLOUDY models

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- ▶ $T = 10^{5.29^{+0.07}_{-0.08}}$ K
- ▶ Constant temperature CLOUDY models
- ▶ O VI and size as constraining factors



Figures/Mid-term/physical-params.png

The Survey

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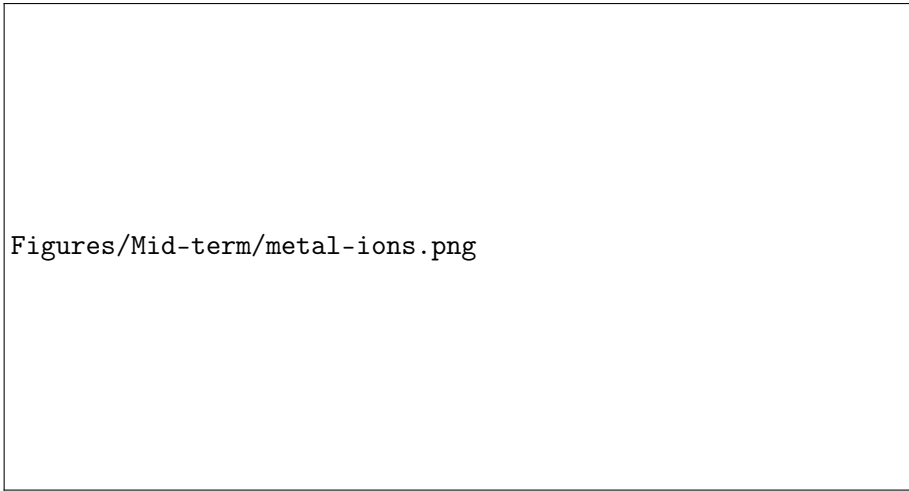
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28 BLA candidates



Figures/Mid-term/metal-ions.png

Figure 8: No. of different metal ions in all the 28 candidate BLAs

References

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

Cen R., Ostriker J. P., 1999, ApJ, 514, 1

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

Fukugita M., Hogan C. J., Peebles P. J. E., 1998, ApJ, 503, 518

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

Shull J. M., Smith B. D., Danforth C. W., 2012, ApJ, 759, 23

Tepper-García T., Richter P., Schaye J., 2013, MNRAS, 436, 2063