Chapter 1

Hunt for BLAs : The Survey

The foremost goal of the current study is to do a survey of BLAs over a large data-set and then estimate their contribution in the closure density of Ω_b. In this chapter we describe our approach to carry out this exhaustive survey.

1.1 Shortlisting the BLA candidates

Danforth et al. (2016) have identified a total of 2611 absorber systems in their study of the low redshift intergalactic medium. We need to find suitable candidates for our survey of BLAs from these 2611 absorbers.

We use two criterias to select BLA candidates for our survey. First, we look for broad Lyα lines in all the 2611 absorbers. For a Lyα line to be adjudged as 'broad', we fix our threshold for b value to be greater than 45 km s^{-1} in the preliminary fitting done by Danforth et al. (2016). Assuming a complete thermal broadening, $b = 45$ km s^{-1} gives a temperature of $\approx 1.2 \times 10^5$ K, which lies in the lower ranges of the temperature of WHIM. By giving this constrain, we get 568 such systems in the complete data-set.

As discussed in section **??**, multiple lines or contaminations from other lines can blend together to give rise to broad absorption features. In such cases, we need to carefully model these broad lines and confirm that these are actually tracing hot collisionally ionised gas phase so that they are indeed probing WHIM and

Figures/metal-ions.png

Figure 1.1: No. of different metal ions in all the 29 absorber systems.

not just cool photoionised phase. We need to perform ionisation modelling for it. To model the ionisation conditions of the absorber systems, we need metal ion column densities. So we search for systems showing metal line absorption in these 568 'broad' systems. We need at least three distinct metal ions (not lines) to better constrain the ionisation state of an absorber system. This sets our second criteria that there should be minimum of three metal ion absorption in the absorber systems. Upon putting this constrain, we get 29 systems having at least 3 distinct metal ions out of 568 already identified systems. Out of these 29 systems, we have already studied one of the absorber in chapter **??**. Table 1.1 lists the lines of sight, redshift of the absorber and the ions detected in the systems these 29 identified BLA candidate absorber systems. Figure 1.1 shows the distribution of different metal ions found in these 29 absorber systems.

1.2 Survey methodology

We have identified 28 additional BLA candidate systems for our survey. We need to do the Voigt profile fitting to the absorption lines identified in these sys-

S. no.	Sight line	z_{abs}	Metal ions
1	1ES 1553+113	0.187731	C III, O VI, N V
2	3C 263	0.063275	C IV, Si III, Si IV
3	3C 263	0.140754	C IV, Si III, O VI
4	3C 57	0.077493	C IV, Si IV, N V
5	H 1821+643	0.170062	Si III, O VI, N V
6	H 1821+643	0.224832	Si III, O VI, C III
7	HE 0056-3622	0.043318	C IV, Si III, N V
8	PMN J1103-2329	0.003975	C IV, Si III, Si IV, N V
9	PG 0003+158	0.386094	C III, O VI, O III, N V
10	PG 0003+158	0.347586	C II, C III, Si II, Si III, O VI
11	PG 0003+158	0.421880	O VI, O III, C III
12	PG 0832+251	0.017520	C IV, Si IV, O I, Si III, C II, Si II, Fe II, Al II, N V
13	PG 1116+215	0.138527	C IV, Si IV, N II, P II, Si III, Si II, C II, O VI, N V
14	PG 1121+422	0.192434	Si IV, C III, Si III, Si II, C II, O VI
15	PG 1216+069	0.006390	O I, Si II, C II
16	PG 1216+069	0.282195	Si III, O VI, C III
17	PG 1222+216	0.054491	C IV, Si III, Si IV
18	PG 1222+216	0.378600	Si III, O VI, O III, C III
19	PG 1259+593	0.046107	C IV, Si III, Si IV
20	PG 1424+240	0.146789	C IV, Si III, O VI, Si IV
21	PHL 1811	0.080837	C IV, Si IV, N II, O I, Fe II, Si II, C II
22	PKS 0405-123	0.167125	Si IV, N II, C III, O I, Si III, Si II, C II, O VI, N III, N V
23	PKS 0637-752	0.161068	Si III, O VI, N V
24	PKS 0637-752	0.417573	Si III, O VI, C III
25	PKS 1302-102	0.094864	Si III, Si II, C II
26	RX J0439.6-5311	0.005602	C IV, Si III, Si IV
27	SDSS J135712.61+170444	0.097767	C IV, Si IV, Si III, C II, O VI
28	SBS 1108+560	0.463201	C III, O I, Si III, Si II, C II, O VI, N III
29	UKS 0242-724	0.063775	Fe II, Si II, C II

TABLE 1.1: Details of the 29 BLA candidate absorber system shortlisted for the survey.

tems. These will give us the column densities and Doppler parameters of the ions in the system and also their redshifts (velocities). We will further use these quantities to model the ionisation conditions in these absorber systems.

The distribution of these quantities can give valuable insights towards our understanding of the intergalactic medium and the baryon content within IGM. As discussed in chapter **??**, that O VI is good tracer of WHIM. O VI absorption is seen in 16 out of these remaining 16 absorbers. For the remaining 12 candidates, O VI is not a non-detection. The O VI 1032, 1038 lines fall out the coverage of the HST/COS FUV channel at redshifts below ~ 0.093854 and all these remaining 12 systems are at redshift below 0.093854. So O VI is not covered in these systems. However, for one system which is along the LOS of PKS1302-102 at $z_{abs} = 0.094864$, the O VI 1038 line was just falling just on the edge of the spectrum where both S/N and sensitivity both low. So, O VI absorption was not considered for this system.

We first model the ionisation conditions in the 16 O VI absorbers and see if we can explain the origin of O VI through photoionisation models using the similar method used for the absorber in chapter **??**. For, the remaining 12 non-O VI absorber, we model the ionisation conditions based on the ions detected in the systems to estimate the density and metallicity in these systems.

Then, we will use the results from this survey to estimate the baryon content in BLAs and their contribution to cosmic closure density, Ω_b, the details of which are described in the upcoming chapter.

The Voigt profile fitting and ionisation modelling results are given in appendix **??** after the references.

1.3 Survey statistics

In this section, we discuss the statistics and results of the survey from Voigt profile fitting and ionisation modelling of the 29 absorber systems.

Figures/ion-component.png

FIGURE 1.2: No. of components identified for H I and different metal ions.

1.3.1 Voigt profile fitting

This survey of 29 absorbers spanned 22 lines of sight. These 22 lines of sight have total H I (Lyman-α) redshift pathlength of $\Delta z = 5.561$. A total of 413 absorption lines were identified and fitted with Voigt profiles. These 413 lines shown absorption from 15 different metal ions apart from H I absorption. The figure 1.2 shows the total number of components identified for each species. For studies similar to current one, it is very insightful to describe the line density per unit redshift ($d\mathcal{N}/dz$) and bivariate distribution of the absorbers with respect to column density and redshift ($\partial^2\mathcal{N}/\partial N\ \partial z$) (see e.g. Danforth et al. (2016); Penton et al. (2000); Tilton et al. (2012)). However, since our current sample is not statistically large, we don't describe these metrics while discussing the statistics of the survey.

1.3.1.1 H I absorbers

We have identified 97 H I components in our survey across 29 absorbers. The figure 1.3 shows the distribution of column densities and redshift of these 97 components. These components span seven orders of magnitude of column densities

Figures/HI_distribution_survey.png

FIGURE 1.3: Distribution of column densities (left panel) and redshift (right panel) of 97 H I components.

starting from $\sim 10^{13}$ to 10^{19} cm^{-2}. We have many absorbers with the column densities in the range $10^{13} - 10^{15.5}$ cm^{-2} but current sample is incomplete at rare large column density systems. In our current sample, we see H I absorption till $z \sim 0.45$. In redshift space also, we have more systems at lower redshifts ($z < 0.2$) and only few absorbers at higher redshifts.

Distribution of Doppler parameters

The figure 1.4 shows the distribution of Doppler b parameters of the 97 H I components. The vertical dashed line marks the cutoff for the line to be called as 'BLA' at b=40 km s^{-1}. Assuming a complete thermal broadening, b = 40 km s^{-1} gives a temperature of 10^5 K. Out of 97 components, 37(34) components have Doppler parameters in excess of 40(45) km s^{-1}. Some components show large Doppler widths of above 100 km s^{-1}, for these components only saturated Lyα lines are seen, making the identification of velocity substructures of these lines difficult. This results in the large b values for these lines.

Figures/b_HI_distribution_survey.png

FIGURE 1.4: Distribution of b parameters of 97 H I components.

Temperature estimation using Doppler parameters

We make an estimate of the temperature of the absorbers directly from their Doppler parameters as done for the absorber in chapter **??**. To do so we need the H I lines to be fairly aligned with some other metal ion. Because, if the species are aligned, then we can asssume that they are co-spatial, so that there non-thermal broadening could be assumed to be same. However, we need to be cautious that aligned species need not be co-spatial always. HST/COS data may have wavelength calibration errors of 15-20 km s^{-1}, which could be as high as few resolution elements (Wakker et al. 2015). So, we consider species as aligned if they are separated by less than 20 km s^{-1} in velocity within the fitting errors. We use O VI as the metal specie for estimating the temperature.

We plot the b(O VI) vs b(H I) in figure 1.5 for the 17 absorbers. The orange dashed line corresponds to points where b(H I) = 4b(O VI) which is the case for pure thermal broadening, i.e. non-thermal contributions are zero. The blue marks the region where the non-thermal broadening dominates the line broadening. This is b(H I) = b(O VI) line. And vertical green dashed line marks our cutoff for the

Figures/bHi_vs_BOvi.png

FIGURE 1.5: b(O VI) vs b(H I) plot. The orange dashed line is the b(H I) $= 4b$(O VI) line and blue dashed line shows the b(H I) $= b$(O VI) line.

line to be called as BLA. Now, we can estimate the temperature for a system if the b values of these two species lies within these orange and blue lines given that they are aligned.

We could estimate the temperature for 7 components where H I and O VI were aligned. We list the details of these systems in table 1.2. This estimation of temperature is important in our estimation of Ω_b(BLA) (see section 2.2.1).

N(H I)-*b*(H I) distribution

We plot the H I column density with Doppler parameter in figure 1.6. We observe that lines with large Doppler widths are found within narrow range of column densities towards the lower end. It could possibly be because large b values indicates the presence of high temperature gas, where neutral fraction of Hydrogen will be small. We also see that the lines with large b values have large uncertai-

Sight line	$\mathbf{z_{abs}}$	$\mathbf{\Delta v}$[a] (km s^{-1})	$\boldsymbol{b}$**(H I)** (km s^{-1})	$\boldsymbol{b}$**(O VI)** (km s^{-1})	$\mathbf{b_{th}}$ (km s^{-1})	**log T** (K)
PG 0003+158	0.347586	0 ± 1	62 ± 3	30 ± 2	56 ± 2	5.28 ± 0.05
PG 0003+158	0.386089	14 ± 9	40 ± 4	25 ± 4	32 ± 3	4.80 ± 0.11
1ES 1553+113	0.187764	28 ± 1[b]	51 ± 1	15 ± 3	50 ± 1	5.19 ± 0.04
PG 1222+216	0.378389	4 ± 15	52 ± 4	34 ± 13	41 ± 6	5.00 ± 0.17
PG 1222+216	0.378389	18 ± 4	43 ± 1	29 ± 13	33 ± 6	4.81 ± 0.19
PG 1116+215	0.138527	4 ± 9	71 ± 14	35 ± 3	64 ± 8	5.39 ± 0.21
H 1821+643	0.224981	19 ± 10	84 ± 13	45 ± 1	73 ± 8	5.51 ± 0.16

[a] Velocity separation between H I and O VI components

[b] Even though $\Delta v > 20$ km s^{-1} we still assume it to be aligned.

TABLE 1.2: Details of temperature estimation from Doppler parameters.

nities also. It is because that most of these are coming from absorbers at lower redshifts where only Lyα is covered in COS/FUV, which is saturated. These large uncertainities affect our estimation of Ω_b(BLA) value as discussed in next chapter (see section 2.2).

1.3.1.2 Metal absorbers

We have identified absorption from total of 15 distinct metal ions in our survey. In this section we discuss the statistics of some prominent ions in our sample.

O VI

We identified 35 O VI components in our survey across 17 absorber systems. O VI is the most common ion after Si III (36 components) in our sample, owing to the strong doublet lines at $\lambda_{\rm rest}$ = 1031.927, 1037.616 Å, with fairly large oscillator strengths of 0.1329 and 0.0661 respectively and large cosmic abundance of Oxygen. The figure 1.7 shows the distribution of column densities and redshifts

Figures/NHi_vs_bHi.png

FIGURE 1.6: N(H I) vs b(H I) plot for the 97 H I components. The vertical black dashed line denotes our threshold for line to be considered as BLA.

Figures/OVI_distribution_survey.png

FIGURE 1.7: Distribution of column densities (left panel) and redshift (right panel) of 35 O VI components.

of these 35 components. The O VI coverage starts from $z \sim 0.09$ in the HST/COS FUV G130M grating. Unlike H I, we find O VI columnd densities in narrow range of $\sim 10^{13} - 10^{14.5}$ cm^{-2}.

O VI is a good tracer of WHIM at temperatures in range of $10^5 - 10^6$ K as its ionisation fraction peaks at around $10^{5.7}$ K in collisional ionisation (Gnat & Sternberg 2007). So, many studies of O VI absorbers have been done in detail in the past. Savage et al. (2014) have studied 14 QSO sight lines comprising a total of 56 O VI absorbers showing 85 O VI components. They estimate the baryonic content in warm gas traced by O VI as $\Omega_b(\mathrm{O\,VI})_{\mathrm{Warm}} = (0.0019 \pm 0.0005) h_{70}^{-1}$.

Studies exploring the correlations between star formation and O VI have also been done. In their study, Tumlinson et al. (2011, 2013) found strong correlation between the specific star formation rate and the presence of O VI. They found that star-forming galaxies are surrounded by large halos ionised O VI of sizes ~ 150 kpc, which were not much prominent around galaxies with little to no star-formation.

Figures/SiII_distribution_survey.png

FIGURE 1.8: Distribution of column densities (left panel) and redshift (right panel) of 19 Si II components.

Si II, Si III and Si IV

We find good number of Si absorbers in the form of Si II, Si III and Si IV ions having 19, 36 and 20 components respectively. Si II shows a number of lines in the COS/FUV channel with $\lambda_{\rm rest} = 1526.707, 1304.371, 1260.422$ Å and doublet at 1190.416, 1193.289 Å. Si III has the most components among the metal ions in our sample because of very high oscillator strength of 1.669 at $\lambda_{\rm rest} = 1206.5$ Å. And Si IV shows doublet line at $\lambda_{\rm rest} = 1393.760, 1402.772$ Å. Figures 1.8, 1.9 and 1.10 shows the distribution of column densities and redshifts of Si II, Si III and Si IV respectively.

C II, C III and C IV

C II, C III and C IV are some other common ions found in our survey which shows 23, 26 and 22 components respectively. Absorption from C II is from two transitions with $\lambda_{\rm rest} = 1036.3367, 1334.5323$ Å. The C III line with $\lambda_{\rm rest} = 977.0201$ Å has a high oscillator strength of 0.757 which results in prominent absorption from this

Figures/SiIII_distribution_survey.png

FIGURE 1.9: Distribution of column densities (left panel) and redshift (right panel) of 36 Si III components.

Figures/SiIV_distribution_survey.png

FIGURE 1.10: Distribution of column densities (left panel) and redshift (right panel) of 20 Si IV components.

Figures/CII_distribution_survey.png

FIGURE 1.11: Distribution of column densities (left panel) and redshift (right panel) of 23 C II components.

line, hence it is very common ion found in IGM. C IV shows the absorption in the form doublet lines with $\lambda_{\rm rest} = 1548.2041, 1550.7812$ Å. Figures 1.11, 1.12 and 1.13 shows the distribution of column densities and redshifts of C II, C III and C IV respectively. All the three ions have narrow ranges of column densities with a very few exceptional rare high column density components. We can see in the figure 1.12 that C III can be observed even at lower column densities of $\sim 10^{12.5}$ cm^{-2} because of the large oscillator strength C III 977 transition. C IV doublet lines have a limited coverage in the HST/COS FUV channel as they fall out of the COS coverage at $z \gtrsim 0.15$ which could be seen in figure 1.13.

N V

We find only 14 N V components in our current survey, which could be attributed to the lower cosmic abundance of Nitrogen compared to rest of the prominent metals detected in our survey. It shows absorption from the doublet lines at $\lambda_{\rm rest} = 1238.821, 1242.804$ Å. Figures 1.14 shows the distribution of column densi-

Figures/CIII_distribution_survey.png

FIGURE 1.12: Distribution of column densities (left panel) and redshift (right panel) of 26 C III components.

Figures/CIV_distribution_survey.png

FIGURE 1.13: Distribution of column densities (left panel) and redshift (right panel) of 22 C IV components.

Figures/NV_distribution_survey.png

FIGURE 1.14: Distribution of column densities (left panel) and redshift (right panel) of 14 N v components.

ties and redshifts of N v components. It could also trace gas with high temperature above 10^5 K and could also arise from photoionisation from highly energetic photons with energies in the range of $\sim 50 - 100$ ev.

1.3.2 Ionisation modelling

We have done the ionisation modelling for a total of 39 components in 29 absorbers. Out of this, 25 components are from O vi absorbers and remaining are from non-O vi absorbers. We present the results from ionisation modelling of all these components in this section.

From ionisation modelling, we get the Hydrogen density [1] (n_H) and metallicity (Z) of the absorbers, which dictates the prevalent ionising and physical conditions in the absorber clouds. The figure 1.15 shows these values for all the 39 components plotted against each other. We don't see any correlations between the two quantities which is expected as these independently describe the physical conditions of

1. We use this interchangeably with absorber density, i.e density at that component

`Figures/Z_vs_nH.png`

FIGURE 1.15: Metallicity vs density for all 39 components estimated from ionisation modelling. Red error bars are the O VI components and green error bars are non-O VI components

the absorbers. The O VI absorbers are denoted with red and non-O VI absorbers are marked by green error bars.

However, when we see the variation of these two quantities with the underlying neutral Hydrogen column density (N(H I)) in these components, we see some trends. Figure 1.16 shows the variation of density with N(H I). We see a feeble positive relation between n_H and N(H I) for the components from O VI absorbers. This is expected as higher column density would typically result in higher densities if the sizes of absorbers, ionisation corrections are of similar order. The lack of such correlation in the non-O VI case may be due to less number of components.

Unlike density, we find a negative correlation between the metallicity and N(H I) as shown in figure 1.17 which could be seen for both O VI and non-O VI absorbers. However, again due to less number of components for non-O VI absorbers, it less evident in them. This could be explained by the fact that as we get larger N(H I), Figures/nH_vs_NHi.png

FIGURE 1.16: Variation of density with N(H I) for all 39 components. Red error bars are from O VI absorbers and green error are from non-O VI absorbers

Figures/Z_vs_NHi.png

FIGURE 1.17: Variation of metallicity with N(H I) for all 39 components. Red error bars are the O VI components and green error bars are non-O VI components

the column densities of metals do not scale accordingly with N(H I), they remain within the narrow ranges of their distribution. So to recover large N(H I), large line of sight thickness has to integrated with nearly same amount of metals, which results in the drop in metallicity.

1.3.2.1 Origin of O VI in the absorbers

The 17 O VI absorbers have immense importance in our current study so are there ionisation conditions. Based on the results of these 17 absorbers, we estimate the Ω_b(BLA) value as discussed in next chapter. For these 17 systems, having 25 components, we want to find the origin of O VI in these absorbers so that we could see if they are tracing warm-hot gas or cool photoionised gas phase. So, if they arise from a warm-hot plasma, we could infer that the BLA candidate found with O VI could also be thermally broadend. Figure 1.18 shows the bar plot of the inferred origin of these 25 components. 20 of the components could not be explained with photoionisation (PI) models, so possibly tracing a collisional ionised (CI) phase. One of the components, shown agreement with PI models and in 4 components the origin of O VI remained uncertain due to models failing to predict the column densities of other ions detected. The absorber which has this PI component also shows CI origin in another component. Out of the 4 uncertain components, two of them do not show good solution, however, in other two components O VI could be tentatively collisionally ionised, the bad solution is due to large number of ions present in the absorbers where our models fail considerably. However, to be conservative we do not count them in CI case. Table 1.3 gives the details of all these 25 components.

Figure 1.19 shows an example of CI origin of O VI, where other ions could be explained with PI models but not O VI (orange color). Figure 1.20 shows the only example of PI origin of O VI, where we get similar solution for excluding and including O VI cases, indicating that all ions could be explained with PI models. Figure 1.21 shows uncertain case, where our model fails to predict the column densities of other ions as well.

Ionisation modelling of these absorbers shows that the gas in these absorbers, which are possibly tracing WHIM, is multiphase in nature, having ions arising from photoionisation as well as collisional ionisation. In the next chapter, we use these results from ionisation modelling as well as Voigt profile fitting to estimate the baryon content in BLAs.

Figures/OVI_cases.png

FIGURE 1.18: Origin of O VI in 25 components from 17 O VI absorbers.

Figures/s135712-z=0.097869-compII.png

FIGURE 1.19: An example of CI case for an absorber towards the line of sight of SDSS J135712.61+170444 at $z_{abs} = 0.097869$ with log N(H I) [cm^{-2}] = 16.49

Figures/1es1553-z=0.187764-compI.png

FIGURE 1.20: Only example of PI case for an absorber towards the line of sight of 1ES 1553+113 at $z_{abs} = 0.187764$ with log N(H I) [cm^{-2}] = 12.76

Figures/pks0405-z=0.167125-compII.png

FIGURE 1.21: An example of uncertain case for an absorber towards the line of sight of PKS 0405-123 at $z_{abs} = 0.167125$ with log N(H I) [cm^{-2}] = 13.46

Sight line	$\mathbf{z_{abs}}$	**log N(H I)** (cm^{-2})	**Origin of O VI**
3C 263	0.140756	14.49	CI
PKS 0637-752	0.161064	13.60	CI
PKS 0637-752	0.417539	15.41	CI
PG 1424+240	0.147104	14.88	CI
PG 1424+240	0.147104	15.44	CI
PG 0003+158	0.347586	16.10	CI
PG 0003+158	0.386089	14.81	uncertain[a]
PG 0003+158	0.421923	14.17	CI
PG 1216+069	0.282286	16.40	CI
SDSS J135712.61+170444	0.097869	15.01	CI
SDSS J135712.61+170444	0.097869	16.49	CI
1ES 1553+113	0.187764	12.76	PI
1ES 1553+113	0.187764	13.88	CI
SBS 1108+560	0.463207	15.79	CI
SBS 1108+560	0.463207	18.10	uncertain[b]
PG 1222+216	0.378389	15.43	CI
PG 1116+215	0.138527	13.60	uncertain[b]
H 1821+643	0.170006	13.35	CI
H 1821+643	0.170006	13.68	CI
H 1821+643	0.224981	15.13	CI
H 1821+643	0.224981	15.16	CI
PG 1121+422	0.192393	14.34	CI
PG 1121+422	0.192393	17.70	CI
PKS 0405-123	0.167125	13.46	uncertain[a]
PKS 0405-123	0.167125	15.98	CI

[a] Other ions also could not be explained

[b] Bad solution due to many ions

TABLE 1.3: 25 O VI components and origin of O VI in them

Chapter 2

Estimating $\Omega_{\mathbf{b}}$(BLA)

In this chapter we discuss the estimation of the baryon energy density trapped in BLAs, i.e. $\Omega_{\rm b}$(BLA), using our BLA survey which is the cornerstone of the current work. We will statistically estimate the $\Omega_{\rm b}$(BLA) from our survey results. And then we will determine how much BLAs contribute to the baryon budget ($\Omega_{\rm b}$) of the current universe.

2.1 Methodology to determine $\Omega_{\mathbf{b}}$(BLA)

The baryon content of any ion in terms of the current critical density (ρ_{cr}) of the universe can be estimated by integrating over the bivariate frequency distribution of the absorbers as function of column density and redshift of that ion as given in Becker et al. (2011) by following equation :

$$\Omega_{\rm ion} = \frac{H_0 m_{\rm ion}}{c\rho_{\rm cr}} \int \frac{\partial^2 \mathcal{N}}{\partial N \partial X} N dN \tag{2.1}$$

Where, H_0 is the current value of Hubble's constant,

$m_{\rm ion}$ is the the mass of ion,

c is the speed of light in vacuum,

$\mathcal{N}$ is the number of absorbers at column density N and path length X

The path length X is function of redshift (z) and denotes the total absorption path length available for absorption. A non-evolving population of absorbers will show an invariant number density per unit absorption pathlength (Becker et al. 2011). It is defined as :

$$X(z) = \int_0^z (1+z')^2 \frac{H_0}{H(z')} dz' \tag{2.2}$$

(Bahcall & Peebles 1969). Now, assuming a flat ΛCDM cosmology, we can write the Hubble's constant at any z as :

$$H(z) = H_0 \left[\Omega_m(1+z)^3 + \Omega_\Lambda\right]^{1/2} \tag{2.3}$$

with $\Omega_m = 0.31$ and $\Omega_\Lambda = 0.69$ (ref). This gives,

$$X(z) = \int_0^z \frac{(1+z')^2}{\left[\Omega_m(1+z')^3 + \Omega_\Lambda\right]^{1/2}} dz' \tag{2.4}$$

However, whole pathlength of X may not be available for absorption due to the presence of Lyα forest lines, absorption from strong ISM lines and intervening IGM lines also in the spectrum. So, some correction needs to be made to get the unblocked absorption pathlength. To calculate this correction, we have developed an interactive program, where we manually select the wavelength regions showing strong absorption features from the above mentioned lines along each sight line. So we exclude these wavelength regions to calculate the unblocked absorption pathlength.

Now, to get the baryon content of BLAs using equation 2.1, we can use total Hydrogen column density, N(H), and $m_{ion} = \mu.m_H$, where μ is the mean atomic mass in a.m.u. and m_H is the mass of Hydrogen atom. We take $\mu = 1.32$ for $\mathrm{Y_{He}} = 0.2446$ (Peimbert et al. 2016) taking in account the Helium abundance in the universe. But N(H) is not a directly observable quantity, instead we can get neutral Hydrogen column density, N(H I), from observations. So we need the correct for the ionisation of Hydrogen to get N(H) from observable N(H I). This ionisation correction is not trivial and require number of assumptions.

If the gas is collisionally ionised, then we can estimate the hydrogen ionization fraction, which is the ratio of amount of total hydrogen and neutral hydrogen, in equilibrium using the models given by Sutherland & Dopita (1993) which related the ionisation fraction to the temperature of the gas. It gives following relation :

$$\log f_H \approx 5.4 \log T - 0.33(\log T)^2 - 13.9 \tag{2.5}$$

This relation is valid in the temperature regimes of $10^5 - 10^7$ K. Figure 2.1 shows the variation of f_H with T based on above relation . We can use this to convert N(H I) to N(H). However, we need to note that at densities lower than $n_H < 10^{-5}$ cm^{-3}, photoionisation from UV background could result in higher hydrogen ionization fraction. But since we don't have the hydrogen densities in the absorbers, so we could possibly underestimate the f_H in such cases (see Richter (2020); Fang & Bryan (2001) for more details). So this would give us an lower limit on the baryon content in this absorbers. Still, we need the temperature to get the ionisation correction. We could only estimate the temperature where the BLA is aligned with some other ion like O VI. We have only few such cases. In rest of the cases, where we don't have an estimate of temperature, we use the Doppler width, b, of the BLA to estimate the temperature assuming pure thermal broadening. This gives us an upper limit on the temperature of the absorber. Now, $b^2 = 2kT/m_H$, so $T = (m_H/2k)b^2$.

Now, as the neutral fraction of hydrogen is very low at the temperatures in WHIM, we can write :

$$\log f_H = \log\left(\frac{\text{H I} + \text{H II}}{\text{H I}}\right) \approx \log\left(\frac{\text{H II}}{\text{H I}}\right) \Rightarrow \text{H II} = f_H \text{H I}$$

$$\Rightarrow N(\text{H}) = N(\text{H I}) + N(\text{H II}) = (1 + f_H)N(\text{H I}) \approx f_H N(\text{H I})$$

Since don ;t have the bivariate frequency distribution function, we approximate the intergral in equation 2.1, which is commonly done, as :

$$\int \frac{\partial^2 \mathcal{N}}{\partial N \partial X} N dN \simeq \frac{\sum N_{obs}}{\Delta X} \tag{2.6}$$

Figures/fH_vs_T.png

FIGURE 2.1: Hydrogen ionisation fraction as a function of temperature.

Where N_{obs} is the observed column density of the ion and ΔX is the total unblocked pathlength available. Now using equation 2.1, the approximation in equation 2.6 and including ionisation correction we can estimate $\Omega_{\rm b}$(BLA) as :

$$\Omega_{\rm b}(\mathrm{BLA}) = \frac{H_0 \; \mu m_H}{c\rho_{\rm cr}} \sum_{i,j} f_{H_{i,j}} N(\mathrm{H\,I})_{i,j} \Bigg/ \sum_j \Delta X_j \tag{2.7}$$

Where j represents a line of sight and i refers to the absorber along sight line j. So numerator is the sum over all the absorbers and the denominator is summed over all the lines of sight. We use error propogation to find the uncertainity in the value of $\Omega_{\rm b}$(BLA). We consider error in f_H, which depend on temperature, which inturn depend on the measured b values and error in H I column densities.

In the next section we describe the sample of absorbers we will be using to estimate the $\Omega_{\rm b}$(BLA).

2.2 Selecting the absorber samples

We have a total of 29 absorber systems in our survey. These systems have 97 H I components in total. Out of these 97 components, 37(34) components have Doppler parameters above 40(45) km s^{-1}. But as discussed multiple times throughout this work that just having large b value does not ensure we have a 'true' BLA. So we have to carefully select the candidates which are actually BLAs from these 37(34) components to estimate the baryon content of BLAs.

2.2.1 Based on Temperature and Ionisation Modelling

Since, we need the temperature to estimate the ionisation fraction, we consider candidates whose temperatures could be estimated from the Doppler parameters of H I and O VI. We estimated temperatures for 7 systems as discussed in section 1.3.1.1. However, two of the systems had temperatures below 10^5 K, we exclude these candidates as the ionisation correction relation is valid for temperatures above 10^5 K. We put another constrain from ionisation modelling that O VI should be collisionally ionised in these systems, which further ensures that we are tracing warm-hot plasma.

So we get 5 such systems with one-one components each. We call this as sample A and are labelled so in table 2.1. This sample will give us a conservative lower limit on the baryon content in BLAs. Using this sample of absorbers we get $\Omega_{\rm b}(\rm BLA) = 0.0018 \pm 0.05$. Table 2.2 gives the details of the individual sight lines in this sample.

2.2.2 Based on Ionisation Modelling

As discussed in chapter 1 we have modelled the ionising conditions in 25 components of 17 O VI absorbers. And found that 20 of the components could not be explained with photoionisation models, so these could possibly be arising from collisionally ionised gas phase. So these absorbers could potentially be tracing warm hot plasma in WHIM. So we take absorbers where the O VI could not be explained with photoionisation models and has a broad Lyα line ($b > 40$ km s^{-1}). This will give us a little ambitious lower limit on the $\Omega_{\rm b}(\rm BLA)$ value.We have 14 such systems, which have a total of 21 BLA components. However, we exclude one component towards the sight line of PKS 0637-752 at $z_{comp} = 0.161013$ because it has unexpectedly high Doppler parameter of 162 km s^{-1} which affects the estimate of $\Omega_{\rm b}$(BLA) drastically. We get a value of 0.0073 ± 0.0013 for $\Omega_{\rm b}$(BLA) using these 20 BLA components. However, if we include the excluded component we get a value of 0.0093 ± 0.0020 which is about 27% higher than the other value. Table 2.2 gives the details of the individual sight lines in this sample. We could see that individual sight lines have large uncertainities in the $\Omega_{\rm b}$(BLA) value, but the value calculated for whole sample has low uncertainity because of more number of points, hence reducing the statistical errors.

z_{BLA}	b (km s^{-1})	log N(H I) (cm^{-2})	log T (K)	log f_H	log N(H) (cm^{-2})	Sample
			3C 263			
0.140702	87 ± 10	13.49 ± 0.06	5.66	6.09	19.58	B
0.063272	50 ± 6	14.88 ± 0.12	5.18	5.22	20.10	
0.063397	54 ± 6	14.42 ± 0.20	5.25	5.35	19.77	
			PKS 0637-752			
0.161013	162 ± 21	13.60 ± 0.06	6.20	6.90	20.50	B[b]
0.161060	45 ± 1	15.01 ± 0.02	5.09	5.03	20.04	B
0.417645	46 ± 4	14.61 ± 0.07	5.11	5.07	19.68	B
			PG 1424+240			
0.147946	40 ± 3	13.49 ± 0.02	4.99	4.82	18.31	B
			PG 0003+158			
0.347586	63 ± 0	14.20 ± 0.02	5.28[a]	5.41	19.61	A
0.386294	40 ± 4	14.10 ± 0.05	4.99	4.82	18.92	
0.420469	66 ± 10	13.37 ± 0.05	5.42	5.68	19.05	B
0.421837	64 ± 3	14.17 ± 0.04	5.39	5.63	19.80	B
			PG 1216+069			
0.282145	52 ± 3	15.10 ± 0.05	5.21	5.29	20.39	B
0.283054	53 ± 10	13.15 ± 0.18	5.23	5.32	18.47	B
0.005547	95 ± 15	13.56 ± 0.06	5.74	6.22	19.78	
0.006100	81 ± 8	14.76 ± 0.12	5.60	5.99	20.75	
0.006328	106 ± 15	14.79 ± 0.08	5.83	6.37	21.16	
			SDSS J135712.61+170444			

Continued on next page

z_{BLA}	b (km s^{-1})	log N(H I) (cm^{-2})	log T (K)	log f_H	log N(H) (cm^{-2})	Sample
0.097869	46 ± 4	15.01 ± 0.16	5.11	5.07	20.08	B
			1ES 1553+113			
0.187650	51 ± 1	13.88 ± 0.01	5.19[a]	5.24	19.12	A
			PG 1222+216			
0.376596	64 ± 19	13.54 ± 0.11	5.39	5.63	19.17	B
0.377236	52 ± 4	14.34 ± 0.05	5.00[a]	4.85	19.19	A
0.378547	43 ± 1	15.43 ± 0.04	5.05	4.95	20.38	B
0.054437	74 ± 11	14.08 ± 0.15	5.52	5.85	19.93	
			PG 1116+215			
0.138508	71 ± 14	13.60 ± 0.23	5.39[a]	5.62	19.22	A
			H 1821+643			
0.170006	63 ± 3	13.68 ± 0.02	5.38	5.60	19.28	B
0.224900	84 ± 13	13.64 ± 0.11	5.51[a]	5.84	19.48	A
0.226156	62 ± 11	13.48 ± 0.06	5.37	5.58	19.06	B
			PG 1121+422			
0.192397	60 ± 6	14.34 ± 0.09	5.34	5.52	19.86	B
			PKS 0405-123			
0.166496	56 ± 9	13.09 ± 0.06	5.28	5.41	18.50	B
			HE 0056-3622			

Continued on next page

z_{BLA}	***b*** (km s^{-1})	**log N(H I)** (cm^{-2})	**log T** (K)	**log f_H**	**log N(H)** (cm^{-2})	**Sample**
0.043265	85 ± 6	14.02 ± 0.07	5.64	6.06	20.08	
			RX J0439.6-5311			
0.005568	53 ± 6	14.30 ± 0.09	5.23	5.32	19.62	
			UKS 0242-724			
0.063850	46 ± 6	15.17 ± 0.10	5.11	5.07	20.24	
			PG 1259+593			
0.044224	47 ± 12	12.79 ± 0.08	5.13	5.11	17.90	
0.046284	61 ± 7	14.86 ± 0.06	5.35	5.55	20.41	
			PKS 1302-102			
0.094839	46 ± 2	14.96 ± 0.10	5.11	5.07	20.03	
			3C 57			
0.077430	50 ± 4	13.86 ± 0.04	5.18	5.22	19.08	
			PHL 1811			
0.080928	126 ± 23	13.62 ± 0.07	5.98	6.60	20.22	
			PG 0832+251			
0.017505	115 ± 26	14.79 ± 0.07	5.90	6.48	21.27	

[a] Temperature estimated from Doppler parameters

[b] The excluded BLA component discussed in section 2.2.2

Continued on next page

$\mathbf{z_{BLA}}$	***b***	**log N(H I)**	**log T**	**log $\mathbf{f_H}$**	**log N(H)**	**Sample**
	(km s^{-1})	(cm^{-2})	(K)		(cm^{-2})	

TABLE 2.1: CIE properties of 37 BLA components.

Sight line	$\mathbf{z_{em}}$	**log N(H)**	$\mathbf{\Delta X}$	$\mathbf{\Omega_b}$**(BLA)**
		(cm^{-2})		($\times 10^{-2}\ h_{70}{}^{-1}$)
PG 0003+158	0.451	19.61	0.454	0.24 $\pm$ 0.05
1ES 1553+113	0.414	19.12	0.449	0.08 $\pm$ 0.01
PG 1222+216	0.432	19.19	0.424	0.10 $\pm$ 0.08
PG 1116+215	0.176	19.22	0.134	0.33 $\pm$ 0.34
H 1821+643	0.297	19.48	0.239	0.34 $\pm$ 0.23
Total		20.06	1.700	0.18 $\pm$ 0.05

TABLE 2.2: Ω_b(BLA) estimation using sample A

Sight line	$\mathbf{z_{em}}$	**log N(H)** (cm^{-2})	$\mathbf{\Delta X}$	$\mathbf{\Omega_b}$**(BLA)** ($\times 10^{-2}\ h_{70}{}^{-1}$)
3C 263	0.646	19.58	0.535	0.19 ± 0.17
PKS 0637-752	0.650	20.20	0.435	0.98 ± 0.29
PG 1424+240	0.604	18.31	0.579	0.01 ± 0.01
PG 0003+158	0.451	20.14	0.454	0.81 ± 0.17
PG 1216+069	0.331	20.39	0.322	2.05 ± 1.08
SDSS J135712.61+170444	0.150	20.08	0.123	2.64 ± 2.36
1ES 1553+113	0.414	19.13	0.449	0.08 ± 0.01
PG 1222+216	0.432	20.47	0.424	1.89 ± 0.47
H 1821+643	0.297	19.90	0.239	0.89 ± 0.70
PG 1121+422	0.225	19.86	0.203	0.97 ± 0.86
PKS 0405-123	0.574	18.50	0.535	0.02 ± 0.02
Total		21.07	4.298	0.73 ± 0.13

TABLE 2.3: Ω_b(BLA) estimation using sample B

References

Bahcall J. N., Peebles P. J. E., 1969, The Astrophysical Journal Letters, 156, L7

Becker G. D., Sargent W. L. W., Rauch M., Calverley A. P., 2011, The Astrophysical Journal, 735, 93

Danforth C. W., et al., 2016, The Astrophysical Journal, 817, 111

Fang T., Bryan G. L., 2001, The Astrophysical Journal Letters, 561, L31

Gnat O., Sternberg A., 2007, The Astrophysical Journal Supplement Series, 168, 213

Peimbert A., Peimbert M., Luridiana V., 2016, Rev. Mex. Astron. Astrofis., 52, 419

Penton S. V., Stocke J. T., Shull J. M., 2000, The Astrophysical Journal Supplement Series, 130, 121

Richter P., 2020, The Astrophysical Journal, 892, 33

Savage B. D., Kim T. S., Wakker B. P., Keeney B., Shull J. M., Stocke J. T., Green J. C., 2014, The Astrophysical Journal Supplement Series, 212, 8

Sutherland R. S., Dopita M. A., 1993, The Astrophysical Journal Supplement Series, 88, 253

Tilton E. M., Danforth C. W., Shull J. M., Ross T. L., 2012, The Astrophysical Journal, 759, 112

Tumlinson J., et al., 2011, Science, 334, 948

Tumlinson J., et al., 2013, The Astrophysical Journal, 777, 59

Wakker B. P., Hernandez A. K., French D. M., Kim T.-S., Oppenheimer B. D., Savage B. D., 2015, The Astrophysical Journal, 814, 40