4-23-2021

Detecting WHIM Filaments Via Quasar Backlights

Samuel Jacob Bowling

Detecting WHIM Filaments Via Quasar Backlights

by

Samuel Jacob Bowling

An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

to

The Honors College

of

The University of Alabama in Huntsville

April 23, 2021

Honors Capstone Director: Professor Massimiliano Bonamente

Professor - Astrophysics, Physics and Astronomy

Samuel Bowling 4/30/2021

Student Date

Director Date

Digitally signed by James Miller
DN: cn=James Miller, o=UAH, ou=PH & ISEd, email=millerja@uah.edu, c=US
Date: 2021.05.04 10:43:25 -05'00'

Department Chair Date

William Wilkerson Digitally signed by William Wilkerson
Date: 2021.05.05 09:24:55 -05'00'

Honors College Dean Date

HONORS COLLEGE
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Honors College
Frank Franz Hall
+1 (256) 824-6450 (voice)
+1 (256) 824-7339 (fax)
honors@uah.edu

Honors Thesis Copyright Permission

This form must be signed by the student and submitted as a bound part of the thesis.

In presenting this thesis in partial fulfillment of the requirements for Honors Diploma or Certificate from The University of Alabama in Huntsville, I agree that the Library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by my advisor or, in his/her absence, by the Chair of the Department, Director of the Program, or the Dean of the Honors College. It is also understood that due recognition shall be given to me and to The University of Alabama in Huntsville in any scholarly use which may be made of any material in this thesis.

Samuel Bowling
____

Student Name (printed)

Samuel Bowling
____

Student Signature

4/30/2021
____

Date

Table of Contents

Abstract

A large portion of the universe's baryonic content is thought to reside within the Warm-Hot Intergalactic Medium (WHIM), a diffuse plasma with temperatures on the order of $10^5 - 10^7$ K that exists in galactic haloes as well as in large intergalactic filaments (Fukugita and Peebles 2006). While this diffuseness renders the WHIM difficult to directly observe, it is possible to detect WHIM-associated absorption line systems in the spectra of background sources, such as quasars. Surveys in the far-ultraviolet (FUV) have been greatly successful in detecting these systems for cooler phases of the WHIM, around 10^5 K. However, this still leaves the warmer ~ 40% of the WHIM, which requires X-ray observation to detect. Technological constraints render X-ray spectroscopy difficult compared to UV, and to date there have been only seven WHIM candidates discovered in X-ray wavelengths (Bonamente 2019). In this project, one such candidate has been spectroscopically analysed to determine its potential characteristics.

Introduction

The Missing Baryon Problem and WHIM

One of the most intractable problems in cosmology is the so-called “missing baryon problem”. Using knowledge of the relative abundances of elements in the universe, researchers were able to provide a rough estimate of the universe’s total baryonic content. Measurements of high-redshift regions of the universe gave results in good agreement with this estimate (Nicastro et al. 2005). However, surveys of the low-redshift universe came up far short, only returning about 10% of the estimated total (Fukugita et al. 1998). While later observations of Lyman-alpha absorbers were able to increase this fraction to around 40%, a large baryon deficit remained. The search for these missing baryons quickly moved to the space between galaxies, with special focus given to the Warm Hot Intergalactic Medium. The Warm Hot Intergalactic Medium, or WHIM, is a hot, diffuse plasma that forms filaments between galaxies. The WHIM’s diffuse nature renders it extremely difficult to directly observe. In addition, the high temperature of the WHIM, on the order of $10^5 - 10^7 K$, means that any spectral measurements need to be in the far ultraviolet or X-ray bands (Bergman 2007)

Detecting the WHIM

Over the past two decades, two main methods of detecting the WHIM have been developed. The first, involving the dispersion measurements of fast radio bursts, has recently been able to detect a large portion of the WHIM (Macquart et al. 2020). The second, the focus of this paper, is based in X-ray spectroscopy. By looking along the line of sight to distant quasars, one can potentially isolate X-ray absorption features consistent with the WHIM. The main benefit this method has over the fast radio burst method is its sensitivity to temperature. The dispersion measures essentially “catch” every medium the radio waves travel through, rendering it hard to separate the WHIM from cooler gas. In contrast, spectroscopy allows for constraints to be placed on the temperature of the interstellar medium based on the presence of certain ions, as can be seen in Figure 1.

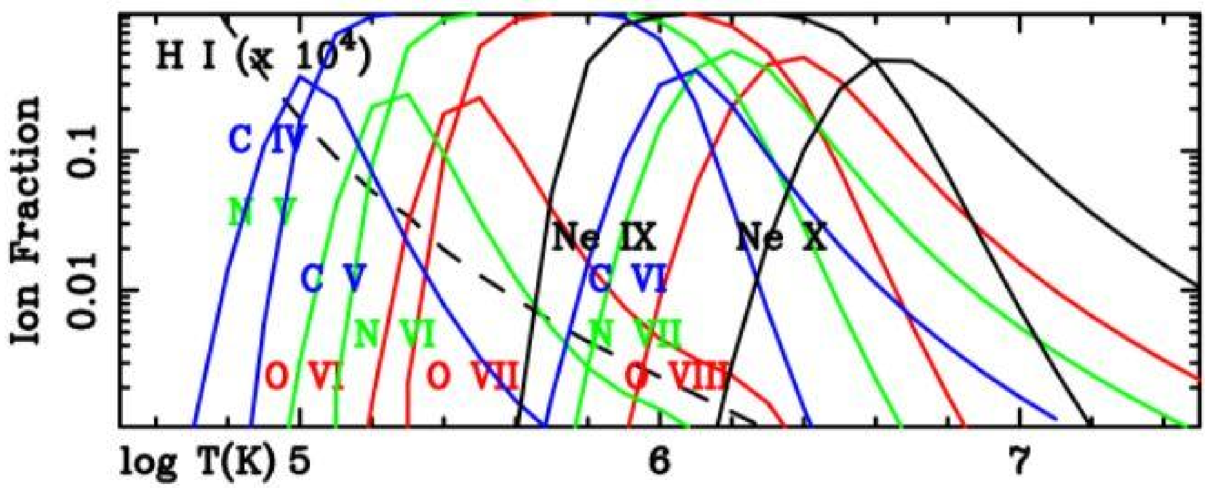

Figure 1: Ionization fractions for several high-temperature metal species (Bonamente 2019)

Methodology

PG 1116+215

The main focus of this paper is an analysis of the *Chandra* X-ray spectra of the quasar PG 1116+215, at redshift $z = 0.177$. *Chandra* observed PG 1116+215 for a total of 88 ks, using the observatory's HRC spectrometer. OVI had previously been detected along the sightline to this quasar, indicating the potential presence of the highly ionized species OVII and OVIII. Focus was placed on locating these two species via their $K\alpha$ lines which, along with other relevant atomic data, can be found in Table 1. Highly ionized metal lines such as these are believed to be characteristic of the WHIM at high temperatures. A previous survey of this candidate had estimated it to be at a redshift of roughly $z = 0.0927$, allowing for the determination of the redshifted wavelengths of the two lines via the relation

$$\lambda_z = z\lambda_0 + \lambda_0$$

with λ_z being the redshifted wavelength, z the redshift, and λ_0 the wavelength for $z = 0$ (Bonamente et al. 2016).

Ion	Wavelength (Å)	Wavelength at $z = 0.0927$(Å)	Oscillator Strength
OVII	21.602	23.605	0.696
OVIII	18.969	20.727	0.416

Table 1: Relevant atomic data for OVII and OVIII (Bonamente 2016)

Spectral Analysis

Spectral analysis was performed using *XSPEC* version 12.11.1. PG 1116+215's spectrum was modeled as a power law, with the spectral lines modeled with a Gaussian, parameterized with total line flux, redshift, and wavelength. A power law model was selected because it relies on relatively few parameters and for its ease of use. The redshifted and rest-frame wavelengths of both lines were modeled over a 1 Å range, and each model parameter was reported to within 2.7 confidence intervals . Initially, the redshift was fixed at $z = 0.0927$, but for the significant OVIII feature found, the redshift was allowed to be free in order for small adjustments to be made to z. Once the best-fit parameters for each model had been found, the equivalent widths of the lines could be determined via the relationship

$$W_\lambda F_\lambda = K$$

where W_λ is the equivalent line width in Å, $F_\lambda = 4 \pm 0.4 * 10^{-4}\ photons\ cm^{-2} s^{-1} Å^{-1}$ is the flux of PG 1116+215 per unit wavelength, and K is the total line flux in $photons\ cm^{-2} s^{-1}$. Once W_λ was known, the column density of the absorber could be found via

$$N = 1.13 * 10^{20} \frac{W_\lambda}{\lambda^2 f} cm^{-2}$$

N being the column density, λ the rest-frame wavelength, and f the ion's oscillator strength (Bonamente et al. 2016).

Results

Galactic Absorption Features

Looking at Figures 2 and 4, two minor oxygen absorption features are apparent. Given their low redshift, these features almost certainly correspond to the Milky Way's interstellar medium. Notably, these two features seem to have roughly identical column densities, indicating equal proportions of OVII and OVIII along this sightline. Going to Figure 1, one can see two temperatures where OVII and OVIII have equal ion fractions: 10^{6}K and $10^{6.4}$K. Given the low value of the column densities, this portion of the interstellar medium likely lies near the cooler temperature.

The OVIII Absorber

The most striking result was the significant OVIII absorption feature found at $z = 0.0905$. Looking at Figure 5, one can easily see the large drop in the spectrum caused by the absorber. In addition, Table 4 shows that the column density for this feature is larger than the galactic absorbers by a factor of roughly 2. Given the relative lack of OVII within this region, as seen in Table 4, one can make a rough estimate of the temperature of this absorber. Given that the ratio of OVIII's and OVII's column densities is of order $\sim 10^{1}$, Figure 1 tells us that the absorber should be at a temperature of roughly $10^{6.8}\,K$, on the higher end of the expected temperature range of the WHIM. As such, the OVIII absorber seems to have high potential to be a WHIM filament.

Conclusion

Surveying the sightline towards PG 1116+215, a significant OVIII absorption feature indicates the potential presence of a WHIM filament at $z = 0.0905$. This feature appears to have a column density significantly higher than that of the galactic interstellar medium at similar temperatures. While not conclusively proving the existence of this WHIM filament, this project helps to showcase the potential benefits of this “backlight” method. With refinements to this technique, quasar backlights may help to put the missing baryon problem to rest once and for all.

Data

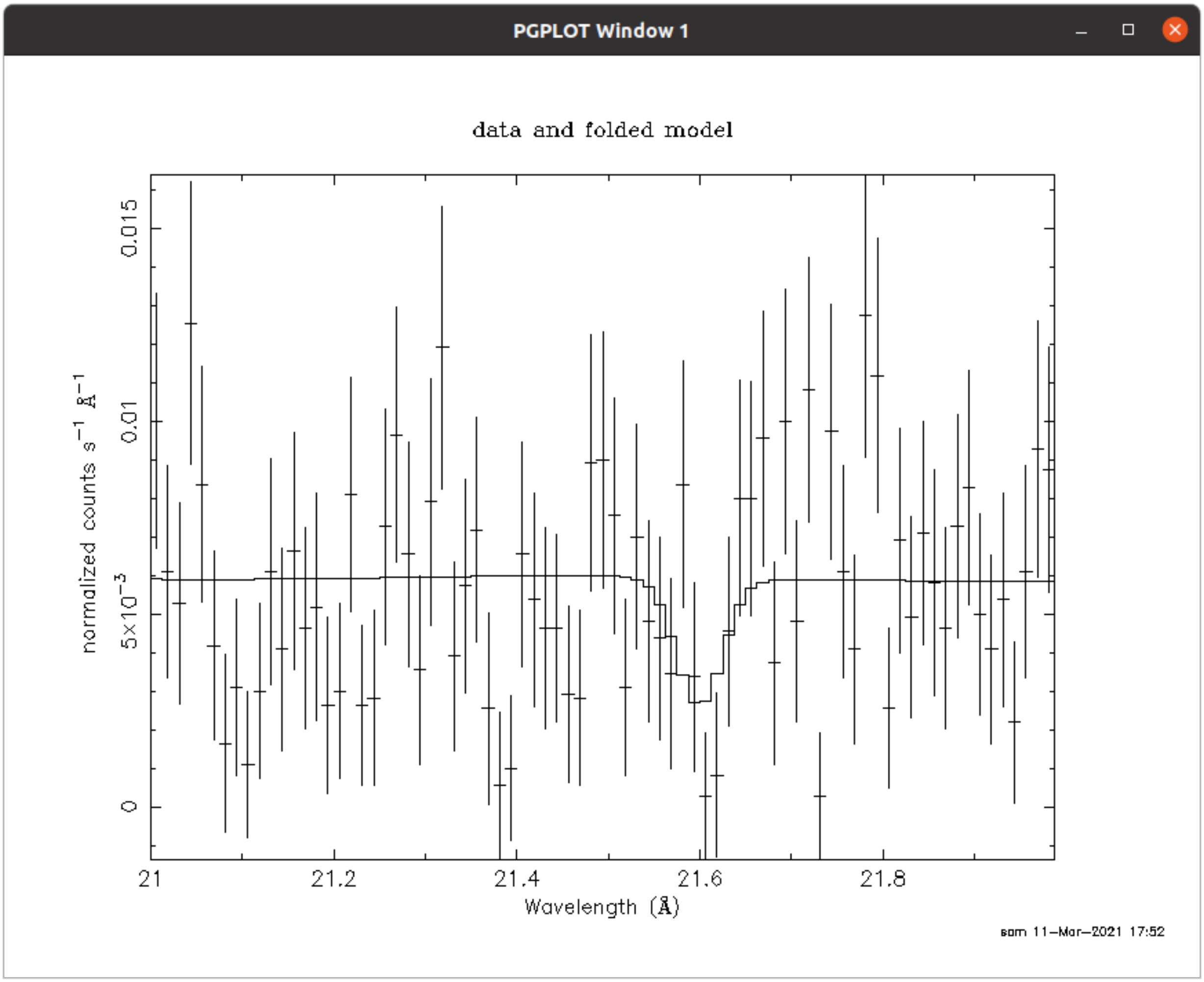

Figure 2: OVII model for $z = 0$. Note the absorption feature at 21.6 Å.

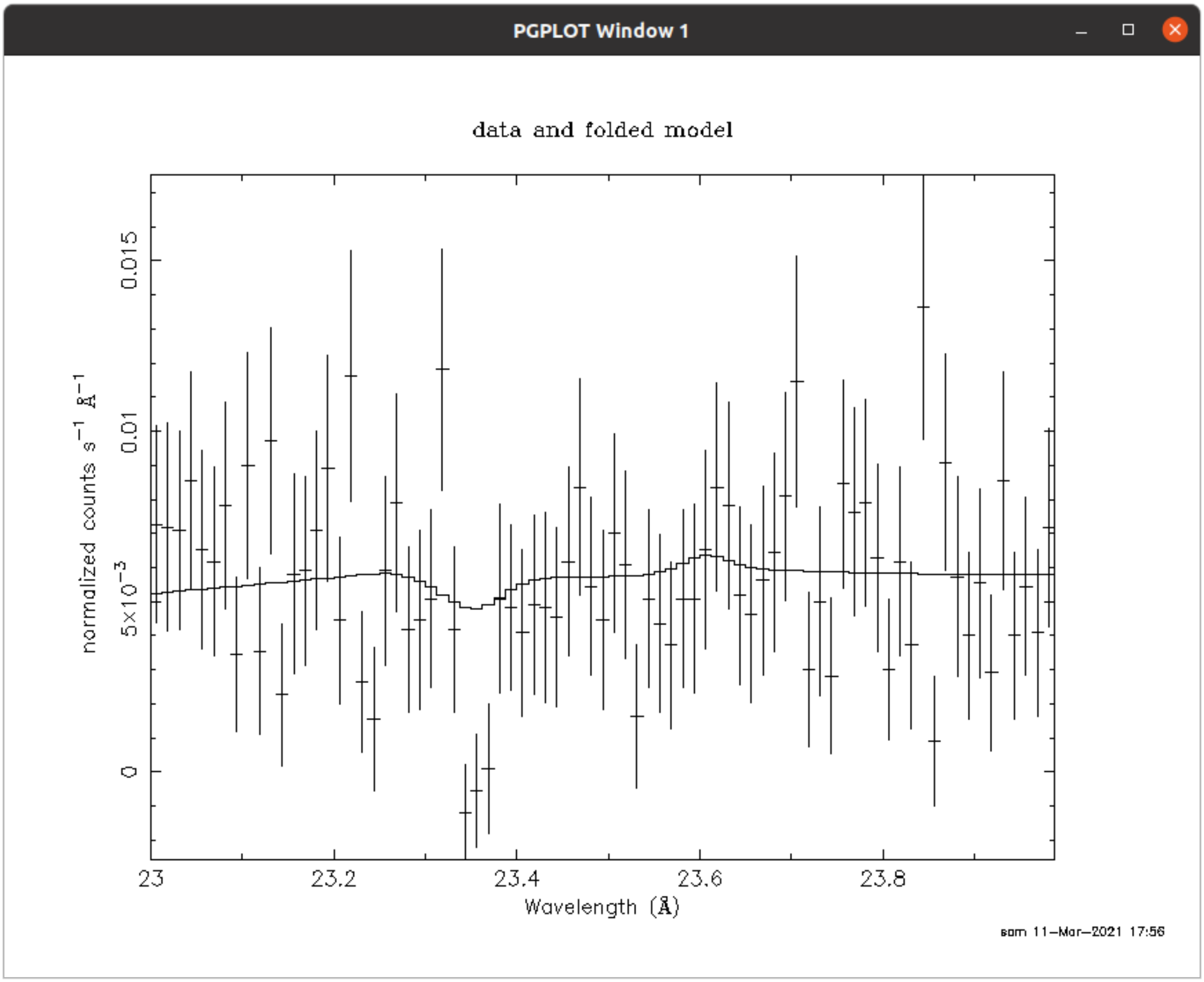

Figure 3: OVII model for $z = 0.0927$. Note the lack of an absorption feature at the redshifted wavelength of 23.6 Å.

Redshift (z)	PhoIndex	Norm (PO)	Line Flux	C-Statistic	Chi-Squared
0	2	$[4.72 * 10^{-3}, 5.67 * 10^{-3}]$	$[-2.39 * 10^{-5}, \; -3.94 * 10^{-6}$	87.63	102.78
0.0927	2	$[4.70 * 10^{-3}, 5.68 * 10^{-3}]$	$[-9.14 * 10^{-6}, 1.54 * 10^{-5}]$	74.06	95.41

Table 2: Model data for OVII. Error bars cover 2.7 confidence intervals.

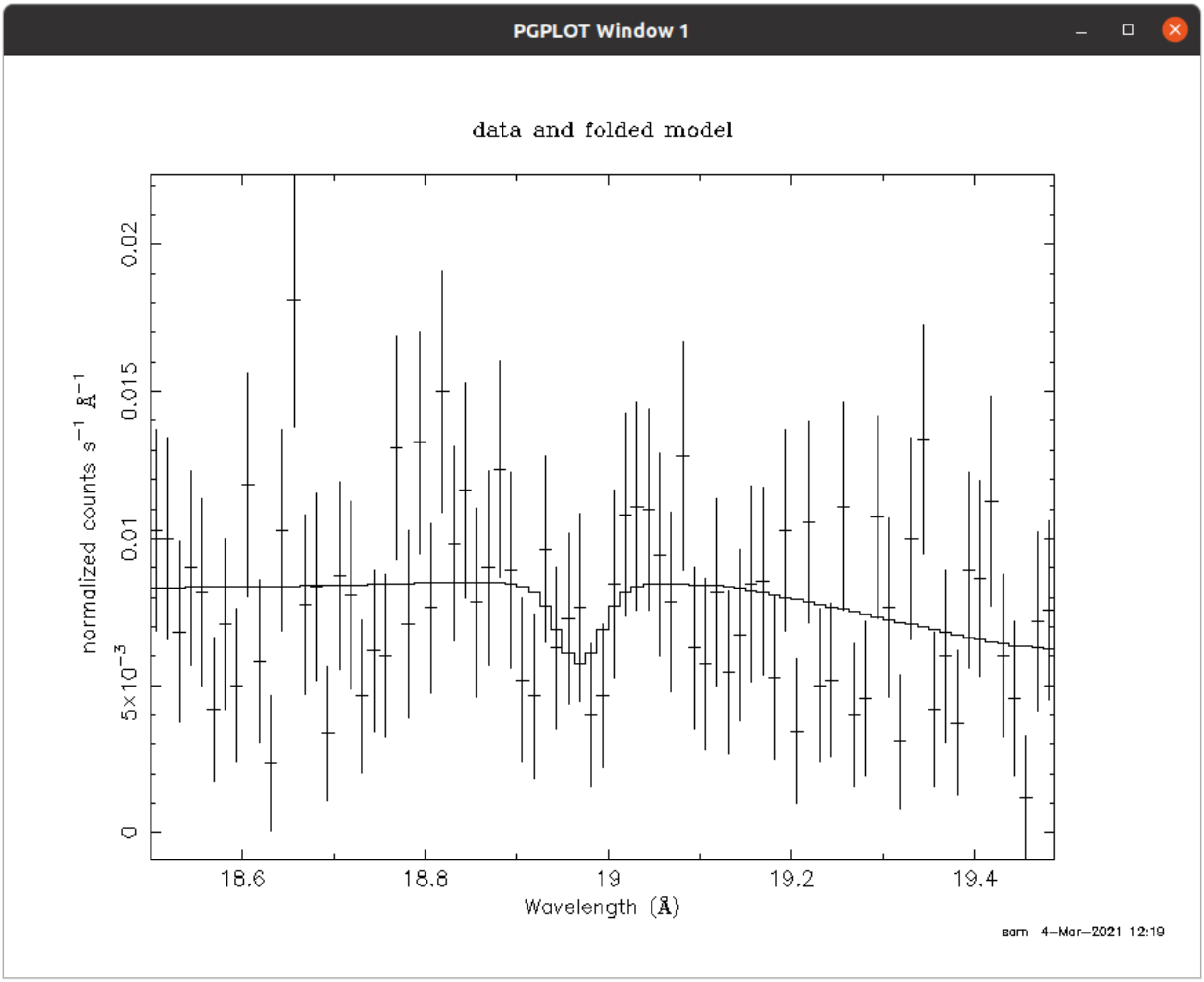

Figure 4: OVIII model with $z = 0$. Note the absorption feature at 18.9 Å.

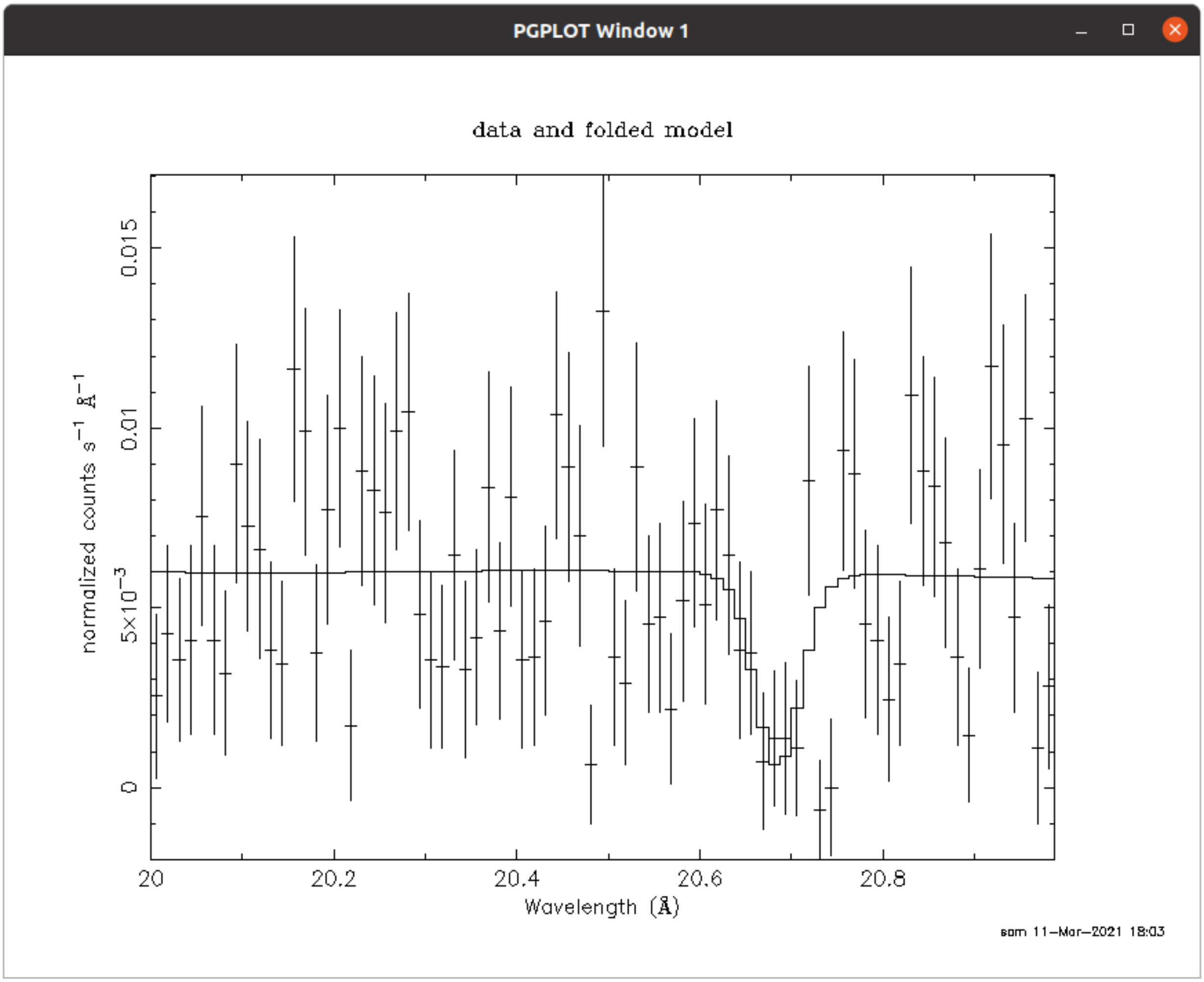

Figure 5: OVIII model with $z = 0.0905$. Note the large absorption feature at 20.7 Å.

Redshift (z)	PhoIndex	Norm (PO)	Line Flux	C-Statistic	Chi-Squared
0	2	$[4.44 * 10^{-3}, 5.17 * 10^{-3}]$	$[-1.45 * 10^{-5}, 3.34 * 10^{-7}]$	72.66	79.24
$[0.0899, 0.0911]$	2	$[4.70 * 10^{-3}, 5.56 * 10^{-3}]$	$[-3.82 * 10^{-5}, -1.47 * 10^{-5}$	93.58	115.97

Table 3: Model data for OVIII. Error bars cover 2.7 confidence intervals.

Ion	Redshift	W_{λ}(Å)	$N(cm^{-2})$
OVII	0	$3.675 * 10^{-2}$	$1.21 * 10^{16}$
OVII	0.0927	$5.725 * 10^{-2}$	$2.72 * 10^{15}$
OVIII	0	$1.888 * 10^{-2}$	$1.34 * 10^{16}$
OVIII	0.0905	$6.350 * 10^{-2}$	$4.99 * 10^{16}$

Table 4: Equivalent widths and column densities for each line.

References

Bonamente, M., J. Nevalainen, E. Tilton, J. Liivamägi, E. Tempel, P. Heinämäki, and T. Fang. 2016. “A Possible Chandra and Hubble Space Telescope Detection of Extragalactic WHIM towards PG 1116+215.” *Monthly Notices of the Royal Astronomical Society* 457 (4): 4236–47. https://doi.org/10.1093/mnras/stw285.

Bonamente, Massimiliano. 2019. “Closing the Gap on the Missing Baryons at Low Redshift with Multi–Wavelength Observations of the Warm–Hot Intergalactic Medium.”

Bregman, Joel N. 2007. “The Search for the Missing Baryons at Low Redshift.” *Annual Review of Astronomy and Astrophysics* 45 (1): 221–59. https://doi.org/10.1146/annurev.astro.45.051806.110619.

Fukugita, M., C. J. Hogan, and P. J. E. Peebles. 1998. “The Cosmic Baryon Budget.” *The Astrophysical Journal* 503 (2): 518–30. https://doi.org/10.1086/306025.

Fukugita, Masataka, and P. J. E. Peebles. 2006. “Massive Coronae of Galaxies.” *The Astrophysical Journal* 639 (2): 590–99. https://doi.org/10.1086/499556.

Macquart, J.-P., J. X. Prochaska, M. McQuinn, K. W. Bannister, S. Bhandari, C. K. Day, A. T. Deller, et al. 2020. “A Census of Baryons in the Universe from Localized Fast Radio Bursts.” *Nature* 581 (7809): 391–95. https://doi.org/10.1038/s41586-020-2300-2.

Nicastro, Fabrizio, Smita Mathur, Martin Elvis, Jeremy Drake, Taotao Fang, Antonella Fruscione, Yair Krongold, Herman Marshall, Rik Williams, and Andreas Zezas. 2005. “The Mass of the Missing Baryons in the X-Ray Forest of the Warm–Hot Intergalactic Medium.” *Nature* 433 (7025): 495–98. https://doi.org/10.1038/nature03245.