משרד החינוך
המינהל הפדגוגי
האגף למחוננים ולמצטיינים

מנחה-עמית: פרופ' אהוד בכר, הטכניון חיפה

# מתכתיות ומקדם מילוי של התווך הבין גלקטי

# Metallicity and Filling factor of the Inter Galactic Medium

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## Research challenges and Goals

The aim of the research was to find the average metallicity and filling factor of the intergalactic medium by calculating the absorption at different filling factors and metallicity arguments.

## Preface:

When observing the universe one notices the brightest sources, which are galaxies. In between the galaxies most of the Universe is empty. Surprisingly, when counting the atoms in the universe, astronomers have found out that only 10% of the atoms lie in galaxies. The remaining 90% therefore are thought to reside in the intergalactic medium (IGM). The detection of these "missing atoms" is difficult. Since they are so rarefied, the light that they emit is extremely faint. One effective way to probe these atoms in the IGM is to observe light from the most remote sources in the Universe and to measure how it is absorbed as it travels through the IGM.

## Theoretical Background-

First we need to define a few terms:

**Metallicity- Z**

Astrophysicists call any chemical element other than hydrogen and helium a metal. The Metallicity, marked in the present work as Z is a measure of the total abundance of metals relative to their abundance in solar-composition gas, which well represents average cosmic abundances. Metallicity is changing as the z grows because that as the z grows we go farther and farther in the universe and as we go in the universe the level of metallicity is decreased. This beaver is defined by the formula $Z(1+z)^{-1}$.

**Red Shift – z**

Due to the expansion of the Universe, distant sources are receding and therefore their radiation is (red)shifted to lower frequencies by a factor of 1+z, where z is the redshift. Given the currently known geometry of the Universe, this redshift is synonymous to a distance measurement. Figure 3.1 shows the connection between redshift and distance.

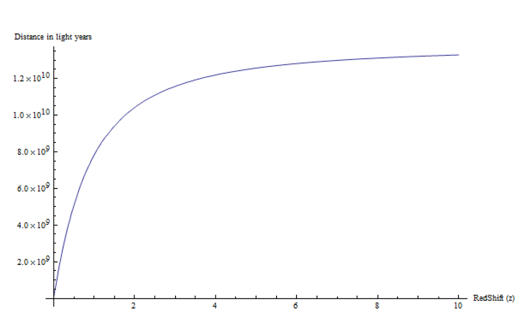

**Figure 3.1.** This figure shows the connection between redshift and distance. The horizontal axes are redshift and the y's are distance in light years.

**Filling Factor- f**

The filling factor of the IGM in our models is the fraction of the volume of the Universe that has gaseous content, whereas the rest of the Universe is assumed to be empty. The filling factor is the ratio of the number of model cells filled with matter to the number of the total cells. Here, we define the parameter f as one over the filling factor. For example a filling factor of f = 25 means that for every 25 cells there is one cell with gas content and 24 Empty ones. The total amount of atomic matter in the universe is known and thus is constant in our models. Therefore, when the value of the filling factor increases (less full cells), the gas density in each filled cell increases.

**Absorption optical depth - $\tau$**

The optical depth of a medium marked with the letter $\tau$ represents the chance ($e^{-\tau}$) for a photon (light particle) to be absorbed in the medium. Absorption in the intergalactic medium as a function of Red Shift at a given photon frequency (or energy) is defined by the formula $\tau(z) = \int Z(z) * n(z) * r(z) * \sigma(z)\, dz$, where Z(z) represents the metallicity, n(z) represents the atom number density in the intergalactic medium, r(z) represents the mean free path of light, and $\sigma(z)$ represents the cross section for absorption of X-ray photons at an energy of 0.5 keV at any given z. The length scale r(z) represents the standard cosmological and geometrical model of the Universe, including the dark energy and dark matter components.

## Abstract

When observing the universe one notices the brightest sources, which are galaxies. In between the galaxies most of the Universe is empty. Surprisingly, when counting the atoms in the universe, astronomers have found out that only 10% of the atoms lie in galaxies. The remaining 90% therefore are thought to reside in the intergalactic medium (IGM). The detection of these "missing atoms" is difficult. Since they are so rarefied, the light that they emit is extremely faint. One effective way to probe these atoms in the IGM is to observe light from the most remote sources in the Universe and to measure how it is absorbed as it travels through the IGM. The aim of our research is to find the average metallicity and filling factor of these IGM. The conclusions from our plots and calculations are that the filling factor and metallicity that best match the observations of absorption in the IGM are between Z = 0.38 to Z = 0.45 and f = 45 to f=60. In these areas the similarity was over 95%.

This research is motivated by a recent work by Professor Behar entitled "Can the soft X-ray opacity towards high redshift sources probe the missing baryons", where absorption of distant X-ray sources indicated the presence of all the missing atoms in the IGM. We use a one dimensional grid to describe the Universe. The starting point of our research is that the matter is spread in "full" and "empty" bins across the universe in a constant filling factor.

## Method

In the research we calculate $\tau(z)$ by applying the formula above. We generated a simulated intergalactic medium in the computer. We assign a redshift value to a 1000 cells from z=0 to z=10 (with redshift steps of 0.01). Subsequently, by applying the formula we find the absorption contribution of each cell.

In the formula $\tau(z) = \int Z(z) * n(z) * r(z) * \sigma(z)\, dz$, we know that n, r, and $\sigma$ as functions of z, so we have one more free parameter in the formula- Z (metallicity). Another free parameter in the simulation is the filling factor. Filling factor influences the resulting $\tau$, because it determines the amount of matter in each cell, or n in the formula, and thus directly the level of absorption.

One of the problems with the filling factor is that we don't know where the "full" cells are. For example we know that for a filling factor of 25 there is 1 full cell for every 25 cells. We don't know which one it is along a line of sight through the intergalactic medium. The full cell and its distance from us determine the value of $\tau$. By using different random values for the filling factors, the position of the full cells change, thus changing the value of $\tau$. Through this method we obtain an ensemble of simulations, which in effect simulate different lines of site (directions) in the IGM. For example figure 4.1.

Our solution to this problem was to draw different possibilities and calculate the average $\tau$.

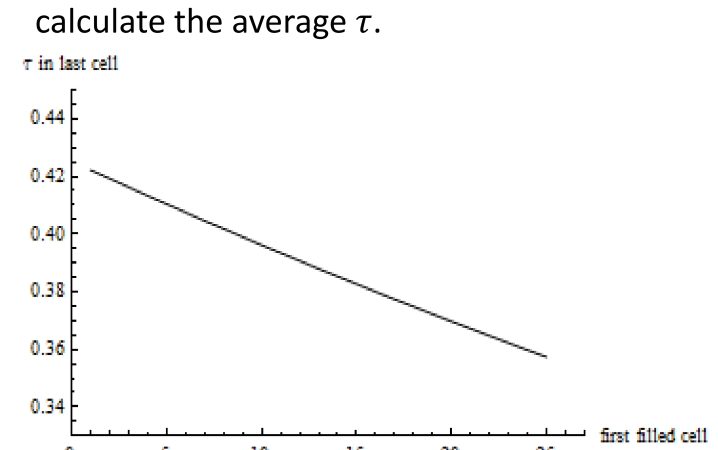


**Figure 4.1** This figure shows the importance of the position of the first filled cell in a given filling factor (25). The horizontal axes are the first full cell and the horizontal axes are "$\tau$".

Our goal in the present research was to find the average metallicity and filling factor of the intergalactic medium that will best match the observed optical depth. We did this by comparing our results to the results of Behar et al. (2011) for both $\tau$at 0.5 keV ($\tau$ = 0.4) and the standard deviation (0.2) of the gamma ray bursts in that sample. Early on, we realized that $\tau$ alone is not enough.

We needed to compare two different indicators to obtain a meaningful constrain on the IGM. The reason for this method is that the average $\tau$ for 100 (or more) draws, with a given filling factor, is only a function of the metallicity. For example see figure 4.2.

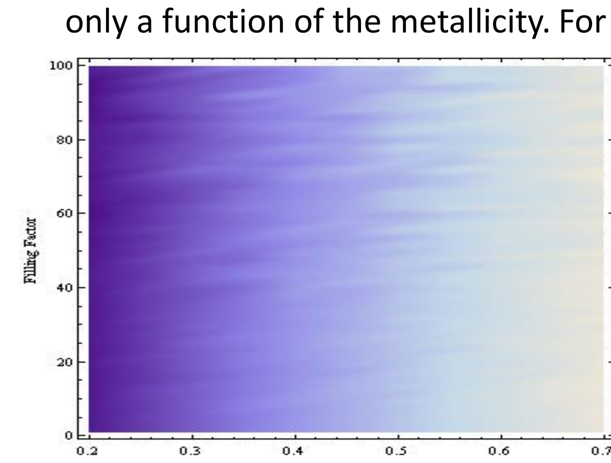


**Figure 4.2.** This plot shows $\tau$ as a function of f and Z; The lighter the color the higher is $\tau$. One can see that for different filling factors the average $\tau$ doesn't change and the metallicity is the only factor.

The way we calculated the standard deviation is according to its standard statistical definition. We took the $\tau$ values in all of the cells at each draw in a certain simulated intergalactic medium (certain filling factor and metallicity) and compared them to the average $\tau$ in the matching cells of the same "intergalactic medium". After that we compared both the average $\tau$ and the standard deviation (denoted here as s) in our simulation to the results from Behar et al. (2011). We plot below the parameter regimes in which there is a good match between the calculations and the observed values.

## Results

In the following we compare the average $\tau$ and standard deviation for different simulated filling factors and metallicitis to the observed values from Behar et al. (2011) that show an average $\tau = 0.4$ and standard deviation of 0.2.

First, we wanted to find the differences between different filling factors in their $\tau$ value. You can see this in figures 5.1 and 5.2.

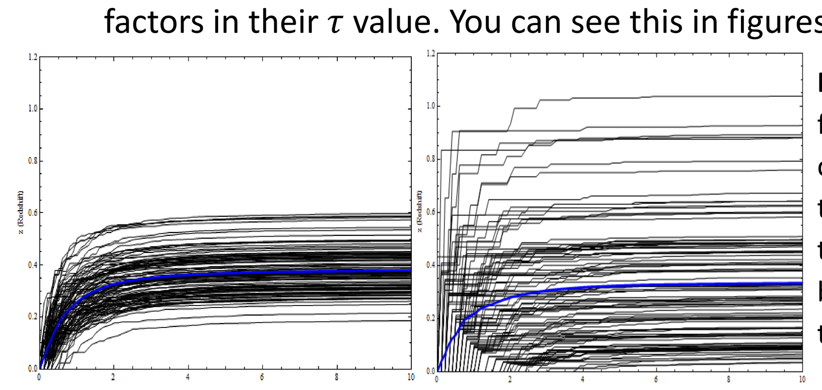

**Figure 5.1.** In both of these figures we plot $\tau$ vs. z. One can see that even though the left plot is for f = 10 and the right one is for f = 80, both have the same average tau(blue line).

This plot shows that the filling factor does uniquely determine the average $\tau$ value. We turn find the relations between different metallicitis and the average $\tau$. The results are plotted in figure 5.2.

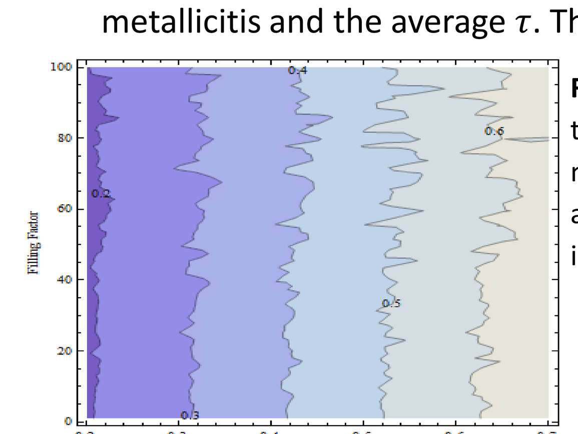


**Figure 5.2.** In this figure the lighter the color the higher is $\tau$. This plot shows that as the metallicity grows $\tau$ grows as well. This figure also shows that the filling factor doesn't influence the average $\tau$.

After we understood the relations between different filling factors and metallicitis to the average $\tau$, we wanted to find the connection between different filling factors and metallicitis to the standard deviation. You can see in figure 5.3 that both the filling factor and the metallicity affect the standard deviation

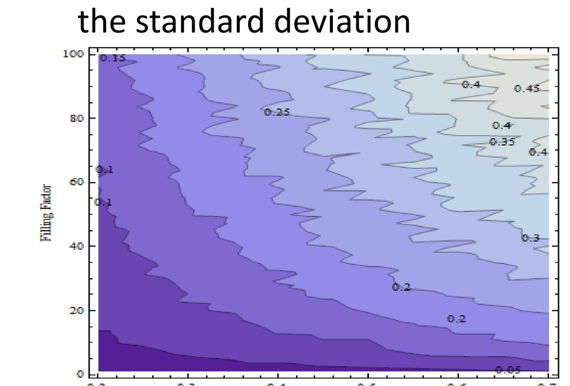


**Figure 5.3.** In this figure, the lighter the color the higher is the standard deviation. This figure shows that there is a strong relation between both $\tau$ and filling factor to the standard deviation.

From this plot, we can see that as the metallicity or the filling factor grows, the standard deviation grows too. We also compared the average $\tau$ from our calculations to the average $\tau$ in Behar et al. (2011) (i.e. $\tau = 0.4$). This comparison is presented in Figure 5.4.

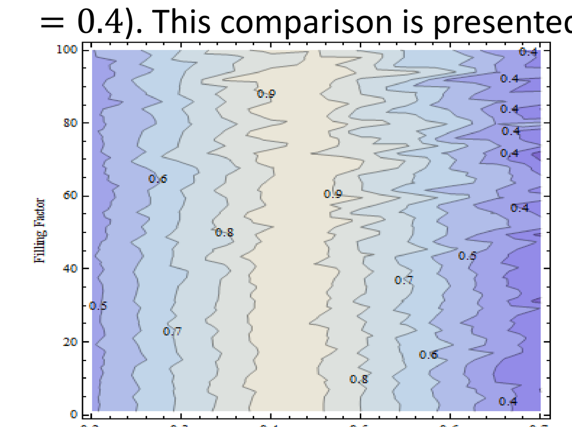


**Figure 5.4.** In this plot we compare the average $\tau$ between the calculations and the observations. The lighter the color, the better is the agreement.

Since we already found that the filling factor alone does not affect the average $\tau$, we do not expect to obtain specific filling factors that match the observations of the IGM better than others, but we can still learn from this plot about the metallicitis that better match the observations. It can be seen that the matching metallicity areas are approximately from Z=0.35 to Z=0.5. After we compared the average $\tau$, we need to also compare our standard deviation calculations to that from the IGM observations. This comparison is presented in figure 5.5.

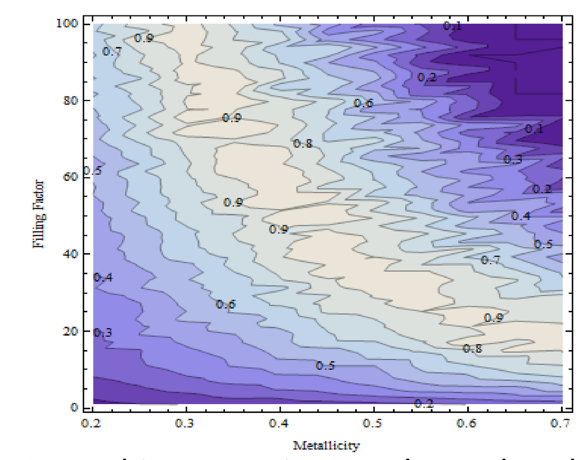


**Figure 5.5.** In this plot we compare the standard deviation between the calculations and the observations. The lighter the color, the better the agreement.

From this comparison we learn that the matching filling factor and metallicity are approximately a linear function of each other. These two figures show us that there is only one area where both standard deviation and average tau will be similar to the observations of the IGM. The function for the average $\tau$ similarity plot is $sim\tau = \frac{0.4-\sqrt{(\tau-0.4)^2}}{0.4} = similarity\ to\ 0.4$, and the function for the standard deviation similarity is $simS = \frac{0.2-\sqrt{(s-0.2)^2}}{0.2} = similarity\ to\ 0.2$ where s is the standard deviation.

After we found out what are the matching areas of filling factor and metallicity in both average $\tau$ and standard deviation, we merge the plots (5.4 and 5.5) into a single one, which gives the combined best-matching values of the metallicity and the filling factor to the ones in the IGM. This plot is presented in figure 5.6. The function for the combined similarity in both $\tau$ and standard deviation to the observations is given by the formula sim = $\frac{sim\tau + simS}{2}$.

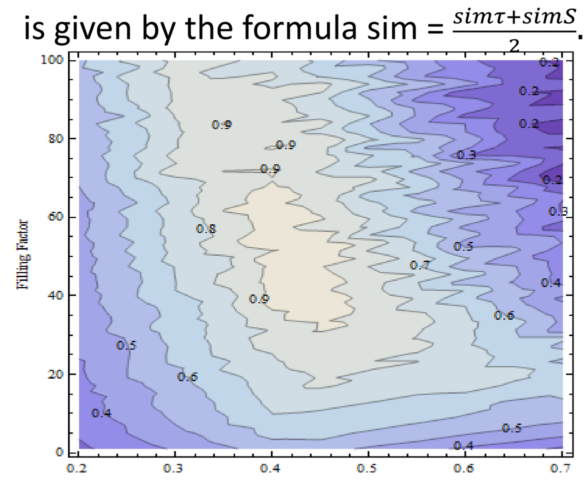


**Figure 5.6.** This plot displays the similarity areas between our calculations of the combined average $\tau$ and standard deviation to the ones from the observations of the IGM. The lighter the color, the better the agreement.

In this plot one can see that the area with the best agreement between simulations and observations is where the metallicity is between Z = 0.35 to Z = 0.5 and the filling factor is between f = 70 and f = 30. One can also see that this area is quite big, and we need to narrow it down. Thus, we zoom into a small area between Z = 0.35 to Z=0.5 and between f = 30 to f = 70 at higher resolution. This plot is presented in figure 5.7, where one can see that there is a 95% match in the areas between Z=0.38 to Z=0.45 from a filling factor of f = 45 to f = 60.

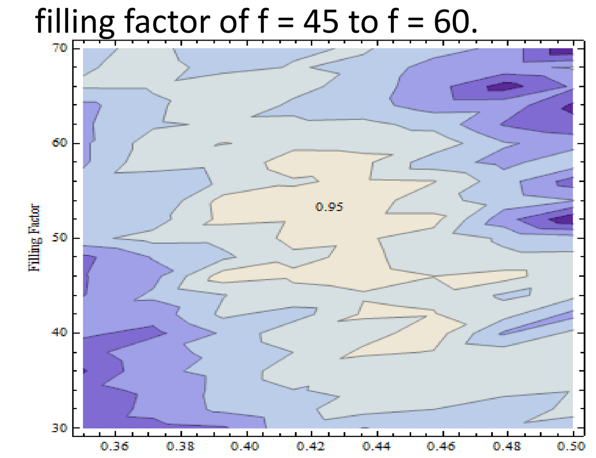


**Figure 5.7.** This plot displays the similarity areas between our calculations of the average tau and standard deviation to the ones from the observations of the IGM. The lighter the color, the better the agreement.

## Conclusion

The conclusions from our plots and calculations are that the filling factor and metallicity that best match the observations of absorption in the IGM are between Z = 0.38 to Z = 0.45 and f = 45 to f=60. In these areas the similarity was over 95%. We can narrow down this areas to a smaller one, but because the errors in the observations and the randomness of our calculations, we won't be able to get a more accurate result over small areas in parameter space.

## Further Research

There are several ideas for further research. The observations we compared our results with were all from the same kind of sources (GRBs) and do not necessarily represent the entire IGM. An idea that is already under research is to look at other radiation sources in the far universe, for example quasars, and to compare our results to those observations. Another thing that can be done is to get more accurate theoretical results by using a stronger computer to run these calculations with more random lines of sight. One more thing that can be done is to use censored statistic. In the observations of the GRBs, many sources featured low absorption that was not properly constrained, so the telescope could only provide an upper limit to the optical depth, which the absorption cannot exceed. This field of research, which uses upper limits for statistics, is called "survival analysis". This approach will be beneficial because it will enable the estimate of average $\tau$ and standard deviation for these sources as well.

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