

Documentation for the intergalactic radiative transfer code

IGMTRANSFER

Version 1.2

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1 Introduction

IGMTRANSFER is a numerical code written in Fortran 90/95, intended for simulating the radiative transfer (RT) of light in the vicinity of the Ly α line through the intergalactic medium (IGM). Originally written with the purpose of investigating how the IGM close to Ly α emitting galaxies reshapes the emission line, it can also be used to probe the general transmission properties of the IGM, thus making it useful in simulations of cosmic reionization.

Ly α is a resonant line, meaning that a photon born in the gas surrounding a hot star doesn't escape the galaxy until it has scattered millions of times on neutral hydrogen, constantly changing direction and frequency. To calculate the exact spectrum of Ly α photons escaping a galaxy, the full resonant scattering RT needs to be solved. Once a Ly α photon is in the tenuous IGM, the probability of being scattered is much smaller, yet in general not negligible. Although the physics of scattering in galaxies and that of scattering in the IGM is not inherently different, the difference in physical conditions imposes a natural division of the two schemes: in the dense gas of galaxies, photons are continuously scattered in and out of the line of sight, whereas in the IGM, once a photon is scattered out of the line of sight, it is "lost", becoming part of the background radiation. The probability of a background photon being scattered *into* the line of sight, on the other hand, is vanishingly small. An illustration of this is seen in Fig. 1.

If you haven't already done so, download all the necessary files from the URL github.com/anisotropela/IGMtransfer. Besides this documentation, this repository contains the following files:

IGMtransfer.f90	Main code.
ProcessIGM.f90	Processes the output from IGMTRANSFER.
F_lam.pro	IDL code visualizing the output from PROCESSIGM.
fold[IPF].vim	Three Vim-scripts that structure the contents of the above three codes, if your editor is Vim.
test.in	Example input file for IGMTRANSFER.
testdir/	A subdirectory for example files containing the following two files:
– CellData.bin	Example input data file for IGMTRANSFER, containing the physical parameters of the gas in a snapshot of a cosmological simulation at $z = 3.5$.
– GalData.dat	Example input file containing physical parameters of the galaxies in the snapshot.
toymodel.in	Input file for a small toy model.
toymodel/	A subdirectory containing the following three files:
– CellData.dat	ASCII data file with toy model gas parameters.
– dat2bin.f90	Converts ASCII data to binary, ready for IGMTRANSFER.
– GalData.dat	Data for two toy galaxies.

After the following description of the basic principles and the physics of the main code, the individual programs are explained. A more thorough description is given in Laursen et al. (2011), which represents the work first employing IGMTRANSFER, and in Laursen et al. (2010, my Ph.D. thesis).

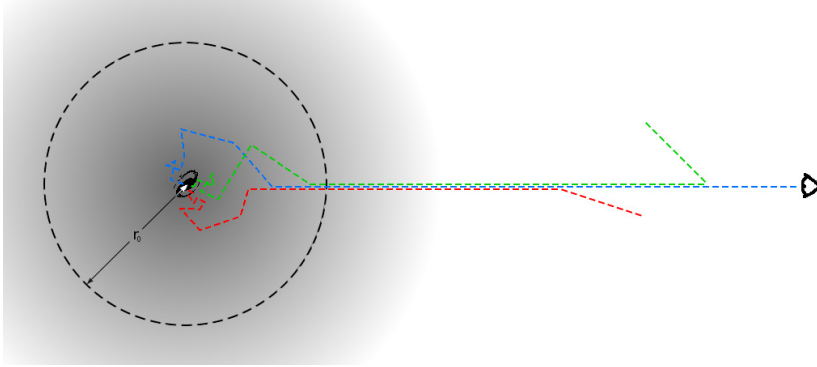


Figure 1: Illustration of the difference between the galactic RT and the IGM RT. Close to the galaxy, photons are scattered both in and out of the line of sight. In the rarefied IGM, photons are mainly scattered out of the line of sight, obviating the need for a full $\text{Ly}\alpha$ RT. The exact value of the distance r_0 from a galaxy to begin the IGM RT is somewhat arbitrary, but is of the order of the virial radius of the galaxy.

1.1 Underlying concepts

IGMTRANSFER performs the IGM RT in a “computational box” with a (possibly adaptively refined) cell-based structure. The final results are obtained by considering the average of the RT performed for many sightlines emerging in many directions from many galaxies. For a given sightline, a (normalized) spectrum is emitted, suffering random absorption lines (i.e. the $\text{Ly}\alpha$ forest) as it is continuously redshifted when receding from the galaxy. When the edge of the computational volume is reached, the sightline continues in a random, inward angle, thus “bouncing” around until the bluest wavelength of the simulated spectrum has been redshifted into the $\text{Ly}\alpha$ resonance (Fig. 2). IGMTRANSFER was originally applied in a non-periodic, spherical volume. The present version (v1.1) includes the possibility of using the full volume of the computational box, and a future version will include the possibility of utilizing periodic boundary conditions, i.e. once the edge is reached, the sightline continues on the opposite side of the box.

The spectrum of each individual sightline is written to an output file which can subsequently be processed by the program PROCESSIGM. This two-step process also enables the user to use the calculated spectra to perform other analyses, e.g. investigate them for the relative abundance of different absorption systems.

1.2 Main output

The final, main output are the two related quantities:

1. the *transmission function* $F(\lambda)$, giving the fraction of light transmitted as a function of wavelength (as an average over many sightlines cast through the cosmological volume), and
2. the average transmission \mathcal{T} of the IGM in a wavelength interval blueward of the $\text{Ly}\alpha$ line.

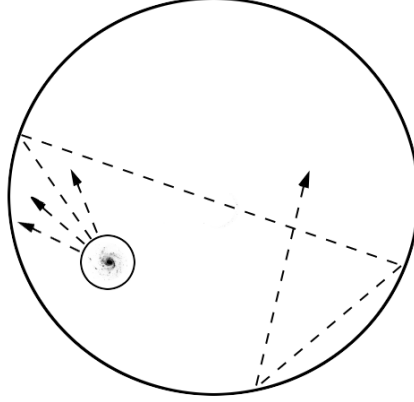


Figure 2: Illustration of how sightlines are cast through the cosmological volume (in the case of a spherical subvolume). To sample sufficiently the full solid angle of 4π around the individual galaxies, `n_los` ($\sim 10^3$) sightlines are cast from each galaxy (of which four are shown here). Each sightline is started at a distance r_0 — which reflects the distance from the center at which the full scattering RT is no longer necessary — from the center of a galaxy and traced until the bluest wavelength of the emitted spectrum has been redshifted into resonance. When the edge of the spherical volume is reached, the ray “bounces” back, i.e. continues in a random inward angle.

1.2.1 Transmission function

The resulting value of $F(\lambda)$ at wavelength λ for a given sightline is

$$F(\lambda) = e^{-\tau(\lambda)}. \quad (1)$$

The optical depth τ is the sum of contributions from all the cells encountered along the line of sight:

$$\tau(\lambda) = \sum_i^{\text{cells}} r_i n_{\text{HI},i} \sigma(\lambda + \lambda v_{\parallel,i}/c). \quad (2)$$

Here, $n_{\text{HI},i}$ is the density of neutral hydrogen in the i 'th cell, r_i is the distance covered in that particular cell, $v_{\parallel,i}$ is the velocity component of the cell along the line of sight, and $\sigma(\lambda)$ is the cross section of neutral hydrogen. Due to the resonant nature of the transition, the largest contribution at a given wavelength will arise from the cells the velocity of which corresponds to shifting the wavelength close to resonance. However, for sufficiently high column density absorbers (the so-called “damped Ly α absorbers”) the damping wing of the profile may cause absorption at velocities quite far from this.

If dust is present in the simulation, $n_{\text{HI}}\sigma(\lambda)$ is replaced by $n_{\text{HI}}\sigma(\lambda) + n_{\text{d}}\sigma_{\text{d}}(\lambda)$. Assuming a spectrum of light $J_{\text{em}}(\lambda)$ escaping a galaxy (simulated, e.g., using Monte Carlo simulations, as in [Laursen et al. \(2009a,b\)](#)), the final, observed spectrum $J_{\text{obs}}(\lambda)$ is then

$$J_{\text{obs}}(\lambda) = F(\lambda) \times J_{\text{em}}(\lambda). \quad (3)$$

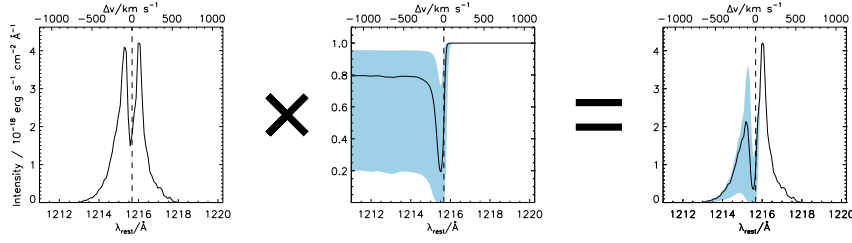


Figure 3: Illustration of the effect of the IGM on the observed Ly α profile emerging from a galaxy at $z \sim 3.5$. Without taking into account the IGM, the two peaks are roughly equally high (*left panel*). However, when the spectrum is transmitted through the IGM characterized by the transmission function $F(\lambda)$ (*middle panel*, with the *cyangrayish* region representing the 68% confidence interval), the blue peak is diminished, resulting in an observed spectrum with a higher red peak (*right panel*). The figure is taken from Laursen et al. (2011).

Figure 3 illustrates this effect. Due to the correlation of the IGM with the source, $F(\lambda)$ is non-trivial close to the Ly α line, but far from the source, or, spectrally speaking, at very blue wavelengths, it becomes a constant function of wavelength (as long as one does not enter an appreciably different redshift epoch).

1.2.2 Average transmission

The transmission function is probably only accurate if you have very high resolution in your simulation; if your cell size is of the order of the virial radius of your galaxies, you will probably overestimate the absorption. However, IGMTRANSFER may still sweeten your life by calculating the *average*, or rather median, transmitted fraction \mathcal{T} in a large wavelength interval blward of the Ly α line. Figure 4 shows such calculated fractions at different redshifts, compared to the observations of Songaila (2004).

1.3 fold[IPF].vim

IGMTRANSFER is written in one single file. If your editor is Vim, *first* time you open the source code use

```
vim -s foldI.vim IGMtransfer.f90
```

This will fold distinct parts of the code into single lines, making it more manageable. To inspect the lines in a fold, go to that fold and press space. To close the fold again, press `zc` while standing in the fold. If you screw something up, exit and open one more time with `-s foldI.vim`.

Similarly, `ProcessIGM.f90` and `F_lam.pro` can be folded with `foldP.vim` and `foldF.vim`, respectively.

If the folds are gone when you open the files next time, try adding these lines in your `.vimrc`:

```
au BufWinLeave * mkview
au BufWinEnter * silent loadview
```

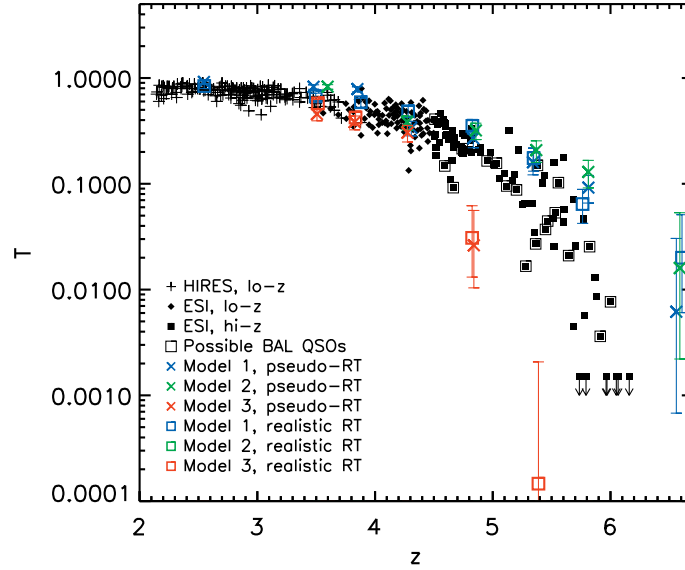


Figure 4: Comparison of observations (*black data points*) and simulations (*colored data points*) of the transmitted flux blueward of the $\text{Ly}\alpha$ line as a function of redshift. The figure is taken from Laursen et al. (2011), but the observed data points are from Songaila (2004).

2 IGMTRANSFER

2.1 Input parameters

The main input parameters are given in an input file; for the example simulation, this file is called `test.in`. The individual input parameters are explained below and summarized in Table 1. Additionally, two data files containing the physical parameters of the gas and the galaxies, respectively, are required. The contents of these are explained in Sec. 2.2 and Sec. 2.3, respectively.

`indir`, `subdir`, `CellData`, and `GalData`

The name of the files containing the gas data and the galaxy data are given in the keyword `CellData` and `GalData`, respectively. These files are supposed to be put in a directory, the name of which is given by the keyword `subdir` which, in turn, is a subdirectory of a mother directory given by `indir`.

`outdir` and `Ioutfile`

The output of IGMTRANSFER is a file with the name given by the keyword `Ioutfile`. It is put in a directory, the name of which is also given by `subdir`, but which is a subdirectory of the directory given by `outdir`. If you want the data files and the output to be in the same directory, simply give the same name to `indir` and `outdir`. Using two different directories, however, may be useful if you wish to save the output on a desk which is backed up.

Poutfile

The output from IGMTRANSFER is processed by the program PROCESSIGM. While the average transmission \mathcal{T} (Sec. 1.2.2) is written to standard output, the transmission function $F(\lambda)$ (Sec. 1.2.1) is written in a text file, the name which is given by the keyword **Poutfile**. This data can be visualized by means of the IDL code F_LAM.

n_write

The number of sightlines traced between each time IGMTRANSFER writes its output.

n_los

The number of sightlines traced per galaxy.

SpecRes

Number of bins into which the spectral range is divided.

BW

Two-element vector giving the lower and upper values of the wavelength interval in Ångström to be propagated through the IGM.

BW_stat

Two-element vector giving the lower and upper values of the wavelength interval in Ångström to be used for calculating \mathcal{T} . In principle, the lower value, **BW_stat**(1), could be set equal to **BW**(1). However, due to the rather broad damping wing of $\text{Ly}\alpha$, as well as the peculiar motion of the gas elements, absorption at a given wavelength is caused by gas occupying a quite large range in real space. For this reason, even though the spectrum is traced until **BW**(1) has been redshifted into resonance, the average absorption will begin to decrease some Ångström before. Thus, it is probably best to omit the bluest ten Ångström or so, depending on the redshift¹.

The higher value of **BW_stat** should be sufficiently far from the $\text{Ly}\alpha$ line center that the state of the IGM — i.e. its density, temperature, ionization state, and velocity field — is not correlated with the source. If you want to be, say, 1 Mpc away from your sources at a redshift of 5, then $\Delta\lambda = \lambda_0 H(z=5) (1 \text{ Mpc})/c = 2.3 \text{ Å}$, i.e. **BW_stat**(2) $\simeq 1213 \text{ Å}$.

If you want to compare to the sample of transmissions by Songaila (2004), use the interval [1080, 1185] Å.

f_rvir

As discussed in the introduction, the sightlines should be started sufficiently far from the center of the galaxies that scattering *into* the line of sight is much less probable than scattering *out of* the line of sight. Denoting this distance r_0 , if r_0 is too small, or too large, absorption will tend to be over- or under-

¹In real observations, the reason for not using too blue wavelengths is both not to enter the $\text{Ly}\beta$ resonance and not to enter an appreciably different redshift epoch; these complications are of course not present in IGMTRANSFER.

estimated, depending on whether the immediate surroundings of the galaxies on average cause more or less absorption than the general IGM. Of course r_0 depends on the galaxy in question, in particular its size, as well as the general state of the circumgalactic gas. However, as argued in Laursen et al. (2011), when measuring r_0 in terms of the virial radii of the galaxies, r_0 for the different galaxies become comparable to each other, and through a convergence study it was found that, at least at the redshifts probed in that study ($z \sim 2.5$ to ~ 6.5), setting $r_0 = 1.5r_{\text{vir}}$ gave meaningful results. *The keyword `f_rvir` specifies the number of virial radii at which to start the sightlines.*

`r_eff`

IGMTRANSFER was originally constructed to perform the RT in a spherical subvolume of a box, with the radius of the sphere given by `r_eff` $\in [0, 1]$, the fraction of the half the side length of the box (i.e. the largest possible sphere has `r_eff` = 1). In order to use the full box, simply set `r_eff` equal to any value larger than $\sqrt{3}$, so that the sphere encloses the box fully.

`DustType`, `f_ion`

If dust is included in the simulations, the string `DustType` should be set to either ‘SMC’ or ‘LMC’, depending on whether the dust is modeled as dust in the Small or Large Magellanic Cloud (SMC and LMC), respectively. Motivated by observations, the dust density is modeled as being proportional to the density of neutral hydrogen, plus a fraction of the ionized hydrogen (as well as to the metallicity). This fraction is given by the keyword `f_ion`. See Sec. 2.2.6 on how to incorporate dust in the simulation.

`z`, `H_0`, `Omega_M`, and `Omega_L`

The redshift of the simulation, and the present values of the Hubble constant (in $\text{km s}^{-1} \text{Mpc}^{-1}$), matter, and cosmological constant parameters. These values are used to convert the wavelength interval into a physical distance.

Table 1 summarizes the input parameters.

2.2 Gas data

The physical parameters of the intergalactic gas elements are given in one-dimensional arrays in binary form in the file `indir/subdir/CellData`, in a nested, space-filling hierarchy. Each array constitutes one record; these records are displayed in Tab. 2, along with the first record that specifies a few important numbers. The subsequent sections explain in further detail what the numbers mean.

2.2.1 `N_cells`, `D_box`, `ni`, `nj`, and `nk`

The first record consists of the following five numbers:

`N_cells` is the total numbers of cells (of all refinement levels).

`D_box` is the length of the side of the computational box in *proper kpc*. That is, if your simulation is a box of, say, $10h^{-1}$ comoving Mpc, then for $h = 0.7$ a snapshot at $z = 3.46$ will have $D_{\text{box}} = (10^3 \text{ kpc}) / 0.7 / (1 + 3.46) = 3203.075$

INPUT PARAMETERS	
Parameter	Explanation
<code>indir</code> ^c	Mother directory for input data subdirectory.
<code>subdir</code> ^c	Subdirectory containing the data files.
<code>CellData</code> ^c	Binary file containing physical parameters of the gas.
<code>GalData</code> ^c	Text file containing the galaxy data.
<code>outdir</code> ^c	Mother directory for output subdirectory.
<code>Ioutfile</code> ^c	Output file of IGMTRANSFER, and input file for PROCESSIGM.
<code>Poutfile</code> ^c	Output file of PROCESSIGM.
<code>n_write</code> ⁱ	Number of sightlines traced between each output.
<code>n_los</code> ⁱ	Number of sightlines per galaxy.
<code>SpecRes</code> ⁱ	Spectral resolution in #bins.
<code>BW</code> ^d	Two-element vector giving the lower and upper limit of the wavelength interval for the RT.
<code>BW_stat</code> ^d	Two-element vector giving the lower and upper limit of the wavelength interval in which to calculate \mathcal{T} .
<code>f_rvir</code> ^d	Number of virial radii from the center of a galaxy, from where to begin a given sightline.
<code>r_eff</code> ^d	Radius of sphere in which to perform the RT, in terms of half the side length of the box, i.e. $\in [0, 1]$ for a spherical subvolume, or $> \sqrt{3}$ to use the full box.
<code>DustType</code> ^c	'SMC' or 'LMC', depending on the dust type.
<code>f_ion</code> ^d	Fraction of ionized hydrogen that contributes to the dust density (see Sec. 2.2.6).
<code>z</code> ^d	Redshift of snapshot.
<code>H_0</code> ^d	Hubble constant in $\text{km s}^{-1} \text{Mpc}^{-1}$.
<code>Omega_M</code> ^d	Matter density parameter Ω_M .
<code>Omega_L</code> ^d	Cosmological constant density parameter Ω_Λ .

Table 1: Explanation of parameters given in the input file `test.in`. Superscripts ^c, ^d, and ⁱ indicate character, real (double), and integer, respectively.

kpc^2 .

`ni`, `nj`, and `nk` is the spatial resolution of the base grid. For a regular, unrefined grid, `N_cells` = `ni` × `nj` × `nk`.

2.2.2 LevelString

As already mentioned, IGMTRANSFER includes the possibility of performing the RT with “adaptive mesh refinement” (AMR); that is, a grid where a number of cells are split up into eight cells which, in turn, may be further split up into eight cells, and so on, recursively, for an arbitrary number of times. The criterion for splitting a cell will usually be a density threshold, but can in principle be anything, e.g. density gradient.

In the case of an adaptively refined grid, an array containing the *refinement*

²The example simulation described in Sec. 5 is a spherical simulation of $10h^{-1}$ comoving Mpc at $z = 3.46$, but is actually enclosed in a slightly larger box of `D_box` = 3400 kpc.

CONTENTS OF “CellData”

Record	Explanation
N_cells^i , D_box^d , ni^i , nj^i , nk^i	Total number of cells, total length of computational box in kpc, base grid resolution in x -, y -, and z -direction.
$LevelString^i$	Refinement levels of cells. Optional.
$n_HIString^s$	Neutral hydrogen number density per cm^3 .
$TString^s$	Temperature in Kelvin.
$V_xString^s$	Gas bulk velocity in x -direction in $km\ s^{-1}$, <i>in physical coordinates and with respect to the center of the box.</i>
$V_yString^s$	Gas bulk velocity in y -direction.
$V_zString^s$	Gas bulk velocity in z -direction.
$ZString^s$	Metallicity in terms of Solar. Optional.
$n_HIIString^s$	Ionized hydrogen number density per cm^3 . Optional.

Table 2: Superscripts ⁱ, ^d, and ^s indicate integer, double, and single precision real, respectively. All arrays (***String**) are of size **N_cells**.

level of each cell must also be given. The refinement of a cell is denoted by its refinement level \mathcal{L} , where $\mathcal{L} = 0$ corresponds to the unrefined base grid. Thus, if dx_0 is the length of a base cell, a cell refined ℓ times has length $dx_0/2^\ell$. Proceeding first in the z -direction, then in the y -direction, and finally in the x -direction, the one-dimensional array **LevelString** contains the refinement levels of each cell. If a cell is refined, this mapping continues in a recursive fashion one level below. Figure 5 illustrates the mapping in 2D, while a 3D rendering of a toy grid is seen in Fig. 6. In the directory **toymodel**, an ASCII file **toymodel.dat** containing the relevant cell data for this toy grid is found, along with a snippet **dat2bin.f90** that converts the data to binary form, ready to be read in by IGMTRANSFER. This structure results in a unique ordering of the cells, and thus no x -, y -, and z -positions are necessary.

The other physical parameters are given subsequently in separate arrays, and in the same order (take a look in IGMTRANSFER’s subroutine **ReadData** to see how the records are read).

In order to use IGMTRANSFER with AMR, it must be compiled with the flag “DAMR” (see Sec. 2.4). For a regular, non-adaptive grid, omit the **LevelString** record and compile without the **DAMR** flag. A permitted, but somewhat inefficient, alternative would be to let **LevelString** consist solely of $ni \times nj \times nk$ zeros.

2.2.3 **n_HIString**

Number density n_{HI} of neutral hydrogen in cm^{-3} .

2.2.4 **TString**

Temperature of the gas in Kelvin. Note that in version 1.0 this record contained instead the corresponding frequency Doppler width.

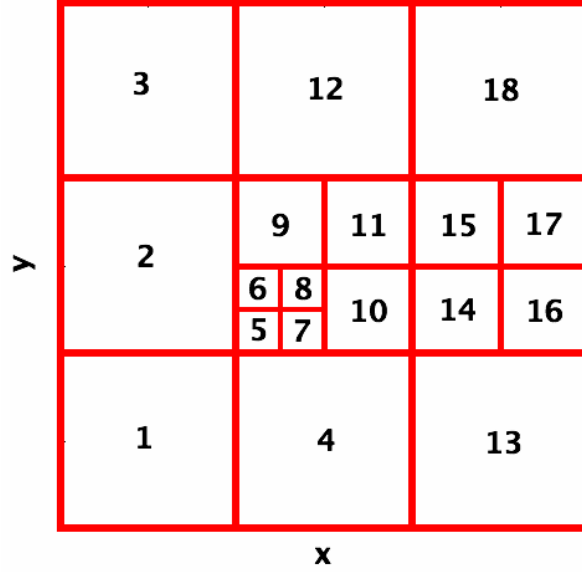


Figure 5: Two-dimensional example of how the AMR grid is represented in the code, with base grid resolution $n_i = n_j = 3$, and maximum refinement level 3. The space-filling curve goes through the grid first in the y -direction, and then in the x -direction. The order of cells are given by the indicated numbers. In the illustrated case, the array `LevelString` would consist of the numbers `[0 0 0 0 2 2 2 2 2 1 1 1 0 0 1 1 1 1 0]`.

2.2.5 `V_[xyz]String`

The arrays `V_xString`, `V_yString`, and `V_zString` contain the bulk velocity of the gas element in the x -, y -, and z -direction, respectively, in km s^{-1} . The bulk velocity is the sum of the elements' peculiar motion and the overall Hubble expansion, and are expressed in physical coordinates with respect to the center of the box. Note that in version 1.0 this record contained instead the velocities in terms of the thermal velocity broadening of the $\text{Ly}\alpha$ line.

2.2.6 `ZString` and `n_HIString`

IGMTRANSFER includes an optional prescription for dust. The dust cross section is expressed as a cross section $\sigma_d(\lambda)$ *per hydrogen nucleus*, with the wavelength dependence given by a fit to extinction curves of dust in the SMC and the LMC by [Pei \(1992\)](#), [Weingartner & Draine \(2001\)](#), and [Gnedin et al. \(2008\)](#)³. Thus, in principle the “dust density” n_d should actually be the hydrogen density n_H , such that the optical depth of dust, as seen by a photon of wavelength λ traveling a distance r through a cell of uniform gas and dust density, is $\tau_d = r n_H \sigma_d(\lambda)$. However, since in general the metallicity in a given cell will differ from that of the reference metallicity Z_0 ($= Z_{\text{SMC}}$ or Z_{LMC}), n_d is scaled

³IGMTRANSFER uses a faster functional form, seen in the subroutine `XsecD`, which is accurate to the sub-% scale around the $\text{Ly}\alpha$ line, and to a few percent in the range $[800, 2000]$ ($[800, 1500]$) Å for SMC (LMC) dust.

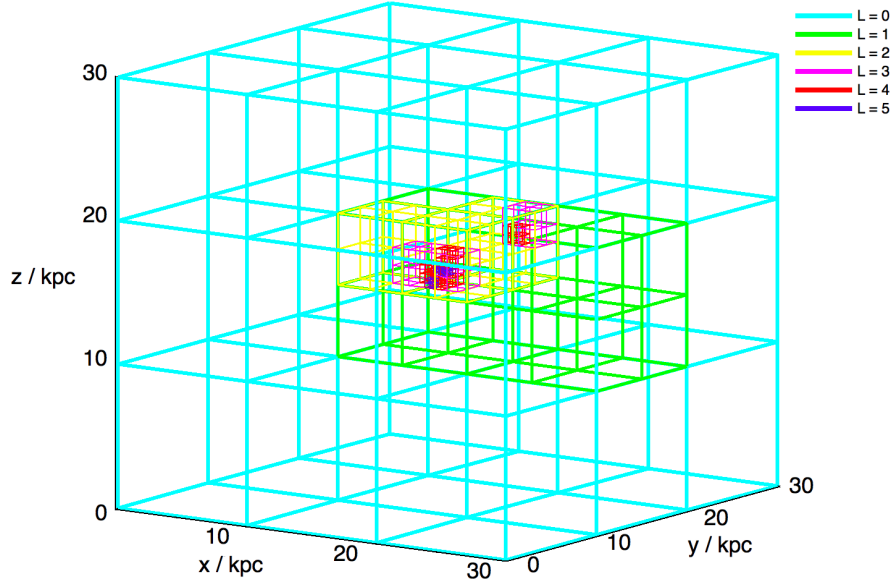


Figure 6: Three-dimensional toy model of a grid with five levels of refinement. Taking a look in the files `toymodel.dat` and `dat2bin.f90` should help you figure out the way the data is organized. See also anisotropela.dk/work/AMRmovie.gif for a 3D rotation.

by the metallicity in that cell, divided by Z_0 . Moreover, since arguably dust tends to be destroyed in regions where hydrogen tends to get ionized, rather than scaling with n_{H} , in Laursen et al. (2009b) we argued that a more realistic quantity is obtained by scaling with n_{HI} , plus some fraction of n_{HII} . Thus, the “dust density” in the i ’th cell is set equal to

$$n_{\text{d},i} = (n_{\text{HI},i} + f_{\text{ion}}n_{\text{HII},i}) \frac{Z_i/Z_{\odot}}{Z_{0,i}/Z_{\odot}}, \quad (4)$$

where Z_{\odot} is Solar metallicity, and $0 \leq f_{\text{ion}} \leq 1$ determines to which degree the ionized hydrogen fraction contributes to the dust density: 0 is complete destruction, 1 is complete survival; in Laursen et al. (2009b) it is argued that setting $f_{\text{ion}} = 0.01$ is a realistic value, and gives $\text{Ly}\alpha$ escape fractions lying roughly midway between using 0 and 1. For more details, see Laursen et al. (2009b), where the value of f_{ion} is also thoroughly discussed.

Thus, to calculate the dust density, two additional records must be provided in “CellData”, namely the metallicity in terms of Solar (`ZString`) and the density of ionized hydrogen (`n_HIIString`). Furthermore, the code must be compiled with the flag “Ddust” (see Sec. 2.4). Note, however, that since by far most of the dust resides in the galaxies, while the largest part of a given sightline goes through the IGM, in general the effect of dust is negligible.

CONTENTS OF “GalData”	
Label	Explanation
x, y, z	x -, y -, and z -position of galaxy in kpc, where the origin is placed in the middle of the box. Note that IGMTRANSFER transforms coordinates from $[-D_{\text{box}}/2, +D_{\text{box}}/2]$ to $[0, D_{\text{box}}]$.
r_vir	Virial radius in kpc.
v_x, v_y, v_z	x -, y -, and z -components of systemic velocity of galaxy in km s^{-1} , in the reference frame of the center of the box. This velocity will be similar to, but in general different from, the bulk velocity of the cell at which the galaxy is centered.

Table 3: Physical properties of the galaxies at which the sightlines are started. In the example simulation these were identified as bound structures satisfying the following criteria: it must not be a substructure of a larger structure, it must have at least 15 star particles, and it must have circular velocity larger than 35 km s^{-1} . These criteria were imposed to ensure sufficient resolution.

2.3 Galaxy data

Every sightline is assumed to initiate just outside a galaxy, where “just outside” is specified by the keyword **f_rvir**, which is the number of virial radii from the center. In Laursen et al. (2011), we found that the correlation of the velocity field and density field with the galaxies causes a non-trivial transmission close to the Ly α line (seen in Fig. 3), and that starting the sightlines ~ 1.5 virial radii from a galaxy gives meaningful results. The galaxies in those simulations each consisted of $\sim 10^3$ to $\sim 10^4$ cells. We emphasize that if your circumgalactic environs are not sufficiently well-resolved, you will probably not find the same shape of $F(\lambda)$; the average transmission \mathcal{T} , on the other hand, is not so sensitive to resolution, and does not depend on your chosen value of **f_rvir**.

The normalized spectrum is emitted at rest wavelength in the reference frame of the center of mass of a galaxy, which in turn may have a peculiar velocity relative to the cell at which it is centered. This spectrum is then Lorentz transformed between the reference frames of the cells encountered along the line of sight. Since the expansion of space is homologous, each cell can be perceived as lying in the center of the simulation, and hence this bouncing scheme does not introduce any bias, apart from reusing the same volume several times for a given sightline. However, since the sightlines “scatter” around stochastically and thus pierce a given region from various directions, no periodicities arise in the calculated spectra.

To calculate the above, the appropriate properties of the galaxies are given in the text file given by the keyword **GalData**, consisting of one line for each galaxy (plus a “header” of an arbitrary number of lines beginning with “#”), and seven rows of data, explained in Tab. 3.

If you are not interested in the properties of the IGM in the vicinity of galaxies (F), but merely in the average properties of the IGM (\mathcal{T}), a similar file may be

constructed, with random initial positions, $\mathbf{r}_{\text{vir}} = 0$, and \mathbf{v}_x , \mathbf{v}_y , and \mathbf{v}_z set equal to the distance from the center of the box times the Hubble constant $H(z)$.

2.4 Compilation

For memory reasons, all parts of the code concerning the AMR structure and the dust are included as “preprocessor directives”, and are compiled only if the appropriate flags are set. To invoke AMR structuring, compile with the flag “-DAMR” (and include a record in the “CellData” file with the refinement levels of the cells); to invoke dust modeling, compile with the flag “-Ddust” (and include two records with the metallicity and the ionized hydrogen density, respectively).

Accordingly, to compile IGMTRANSFER for performing RT in the test data file `testdir/CellData.bin`, which include both AMR and dust, write

```
ifort -O3 -fpp -DAMR -Ddust IGMtransfer.f90 -o IGMtransfer.x
```

or

```
gfortran -O3 -x f95-cpp-input -DAMR -Ddust IGMtransfer.f90 -o IGMtransfer.x
```

or

```
g95 -O3 -cpp -DAMR -Ddust IGMtransfer.f90 -o IGMtransfer.x
```

or

```
pgf90 -O3 -Mpreprocess -DAMR -Ddust IGMtransfer.f90 -o IGMtransfer.x
```

depending on your compiler. The simulation is then run with

```
./IGMtransfer.x < test.in
```

Even if neither of the two optional flags are used, you must still compile with the flags that enable the preprocessing; that is, to compile with neither the AMR nor the dust option, use

```
ifort -O3 -fpp IGMtransfer.f90 -o IGMtransfer.x
```

for the `ifort` compiler, and similarly for other compilers.

3 PROCESSIGM

The output of IGMTRANSFER is a huge file containing a spectrum for each sightline, i.e. a filesize of $4 \times n_{\text{gal}} \times n_{\text{los}} \times \text{SpecRes}$ bytes. The name of this file is given by the keyword `Ioutfile` in the input parameter file.

To extract $F(\lambda)$ and $\mathcal{T}(z)$ from this file, PROCESSIGM is called with the same input file as was used for IGMTRANSFER, i.e.

```
./ProcessIGM.x < test.in
```

where the compiled executable is assumed to have been named `ProcessIGM.x`. The transmission function $F(\lambda)$ is determined by calculating in each wavelength bin the median of all values of $e^{-\tau}$ for all sightlines. To know the dispersion of the transmission for different sightlines, also the 16th and the 84th percentiles are calculated. The result is written in a formatted file, the name of which is given by the keyword `Poutfile` in the input file, with one row for each wavelength bin, and the columns giving wavelength, median, 16th, and 84th percentile. The fifth column is not really used, but gives the average in each bin.

The average transmission \mathcal{T} is determined by calculating first for each sightline j the total transmitted flux in the wavelength interval given by the keyword `BW_stat`, i.e.

$$\mathcal{T}_j = \frac{1}{n_{\text{bins}}} \sum_{i_1}^{i_2} e^{-\tau(i'_{\text{th bin}})}, \quad (5)$$

where i_1 (i_2) is the bin number corresponding to the value of `BW_stat(1)` (`BW_stat(2)`) and $n_{\text{bins}} = i_2 - i_1 + 1$ is the number of bins in the applied interval. Subsequently, the median (and 16 and 84 percentiles) of all sightlines is calculated. The resulting three numbers are the three last numbers written to standard output when running `PROCESSIGM`.

4 F_LAM

The output file from `PROCESSIGM`, given by the keyword `Poutfile` can be visualized using the IDL⁴ code `F_LAM`, which as input takes the same input file as the two previous codes:

```
IDL> .r F_lam.pro
IDL> F_lam, 'test.in' [, outfile=outfile] [, xrange=xrange] [, yrange=yrange]
```

The three optional arguments are:

- outfile:** A string giving the name of the figure produced by `F_LAM`. Default value is `'F_lam.eps'`.
- xrange:** A two-element vector giving the range in Ångström of the plotted wavelength interval. Default value is `[1213,1218]`.
- yrange:** A two-element vector giving the y -range. Default value is `[0,1.1]`.

If everything has gone well, the output of `F_LAM` should be an `.eps` file looking something like the middle panel of Fig. 3.

5 Example simulation

The included example files in the subdirectory `testdir` is a snapshot at $z \sim 3.5$ from (an improved version of) the hydro/gravity-simulations described in Sommer-Larsen et al. (2003) and Sommer-Larsen (2006). This simulation uses a TreePM/smoothed particle hydrodynamics-technique rather than AMR. Accordingly, the physical parameters of the particles have first been interpolated onto an adaptive mesh, using the appropriate smoothing kernels. A Haardt &

⁴Yes, IDL. I... I am sorry. I will translate to Python "at some point".

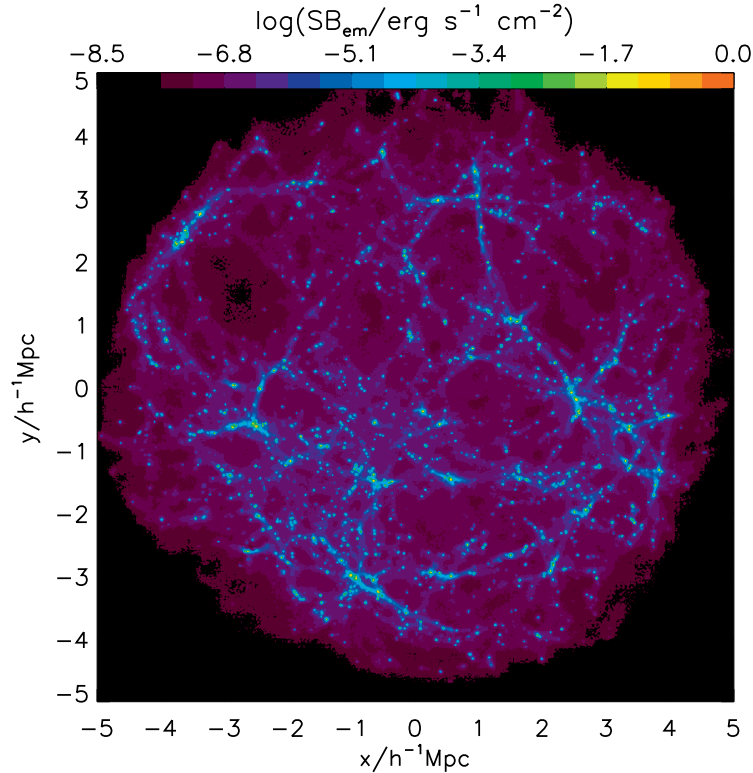


Figure 7: Surface brightness map of Ly α emission in the cosmological volume of the example simulation, i.e. how the volume would look if the Ly α radiation escaped directly towards the observer.

Madau (1996)-like UV background has been assumed, but initiating at $z = 10$ rather than $z = 6$. Furthermore, this simple UV RT scheme has been supplemented by a more elaborate post-processed ionizing UV RT scheme, as described in Razoumov & Sommer-Larsen (2006, 2007).

Figure 7 shows the simulated volume.

5.1 Toy model

Additionally, a subdirectory `toymodel` includes an ASCII file with parameters for the toy grid seen in Fig. 6. The purpose of this is primarily to see how the data are structured; performing the RT in this is possible, but doesn't really give meaningful results. The code `DAT2BIN` converts the ASCII data to binary form in a file that can be read by `IGMTRANSFER`. Note that the data do not include dust, so `IGMTRANSFER` will have to be compiled with the `DAMR` flag, but without the `Ddust` flag.

6 Acknowledgments

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7 License and citing

IGMTRANSFER and its associated programs are free software, distributed under the [GNU General Public License](#), i.e. it may be freely distributed, copied, and even modified, as long as any changes in distributed versions are indicated. For applications of IGMTRANSFER leading to publications, please cite [Laursen et al. \(2011\)](#).

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