The gaseous structure of a halo

In the following you will analyse the distribution of gas from a galaxy from the Illustris TNG-50 simulation (TNG website). You will analyse the same galaxy as in exercise B. So just to remind you: it is a disc galaxy at redshift 0 with a total mass (stars, gas, dark matter) of around 10^{12} $M_{\odot}$. This is comparable to the mass of the Milky Way.

Reading and plotting the data

The gas cells in and around the halo are included in the file, `GalaxyFromIllustrisTNG50_Gas_Subhalo521803.txt`.

The columns are:

```
x in kpc
y in kpc
z in kpc
Gas density (in units of 1/cm**3)
Temperature (in Kelvin)
Mass (in Msun)
SFR (in Msun/yr)
HI Mass (in Msun)
OVI Mass (in Msun)
OVII Mass (in Msun)
OVIII Mass (in Msun)
```

The coordinates are centred such that the galaxy centre is in (0,0,0). The gas density, temperature, mass and SFR are evolved in time, when running the simulation. The table also contains the mass in the ions: H I, O VI,O VII and O VIII – these masses have been calculated based on the simulation output (ionization modelling with the CLOUDY code). The ions trace gradually warmer gas (in the order they are listed).

The data can be read in python with the following code:

```python
import numpy
Array = numpy.loadtxt('GalaxyFromIllustrisTNG50_Gas_Subhalo521803.txt')
Pos = Array[:,0:3]
n = Array[:,3]
T = Array[:,4]
M = Array[:,5]
SFR = Array[:,6]
HI = Array[:,7]
OVI = Array[:,8]
OVII = Array[:,9]
OVIII = Array[:,10]
```

(if you would like to learn how to use the hdf5 file format, you can also use the method outlined in the "bonus task 12", see the last page).

Projection plots

To gain intuition, let us first visualize the gas in this galaxy:

Task 1 Create projection plots showing the surface gas density of the galaxy (in units of $M_\odot$ kpc^{-2}). Create one plot with a box size of 20 kpc $\times$ 20 kpc and one with 200 kpc $\times$ 200 kpc.

Task 2 Create projection plots showing the surface density of H I, O VI, O VII, O VIII (again in units of $M_\odot$ kpc^{-2}, and with same box size as above). Comment on the results!

Task 3 Create projection plots showing the surface SFR density of the galaxy. In units of $M_\odot$ yr^{-1} kpc^{-2} (with same box sizes as above).

Spherical profiles

Task 4 Plot the gas density as a function of radius. Use logarithmic spherical shells (as we e.g. used to plot the dark matter density in exercise A).

Task 5 Plot the temperature as a function of radius. Averaged in logarithmic spherical shells.

An analytical formula for the temperature of a galaxy halo

We will now work out an analytical formula estimating the gas temperature of a halo. Imagine a spherical galaxy with a gas mass, M_{gas}, and a total mass, M (consisting of dark matter, gas and stars). The halo has a radius, R. The gravitational binding energy of the gas is

$$W = -a\frac{GMM_{\text{gas}}}{R}, \tag{1}$$

where a is a dimensionless constant, which depends on the density profile (Click here for link).

We will assume that the gas is in equilibrium and at rest, so the kinetic energy of the gas is given by the thermal energy

$$K = \frac{1}{2}M_{\text{gas}}\langle v_{\text{gas}}^2\rangle. \tag{2}$$

If we assume a uniform temperature of the gas, we obtain

$$\langle v_{\text{gas}}^2\rangle = \frac{3k_BT}{2\mu m_p}. \tag{3}$$

In this analytical derivation we will assume the gas to be ionized and have solar metallicity, where we have a mean particle mass of $\mu \simeq 0.6$.

Task 6 Apply the virial theorem, $2K + W = 0$, and show that we can associate the following temperature of the gas in the halo:

$$T = 4.85\times10^5\ \text{K}\times a\times\left(\frac{V}{100\ \text{km s}^{-1}}\right)^2, \tag{4}$$

where $V \equiv \sqrt{\frac{GM}{R}}$ is a measure of the halo circular velocity.

Task 7 The halo, which we are analysing from Illustris TNG-50 has $M_{200} = 8.635 \times 10^{11}$ $M_\odot$ and $R_{200} = 200.8$ kpc. Estimate the halo circular velocity as $V = \sqrt{\frac{GM_{200}}{R_{200}}}$.

Task 8 Assume $a = 1$ and estimate the halo's gas temperature using Eq. 4. How well does this analytical measure of the temperature compare to the temperature profile from Task 5? Comment on similarities and differences!

BONUS exercises

The following exercises are not mandatory:

Task 9 Plot $(\log n, \log T)$ for the gas (use plt.hist2d to show the gas cell's distribution). Identify the star-forming gas in the plot.

Task 10 Create five $(\log n, \log T)$ plots weighted by SFR, H I mass, O VI mass, O VII mass and O VIII mass. Comment!

Task 11 Recently, the CONCEPT code for doing cosmological simulations in Python was released. Try to install the package and run a simulation following the online instructions: `https://github.com/jmd-dk/concept`

Task 12 Some of you mentioned that you would like to experiment with reading in a binary file instead of the .txt file described above. Also attached to this exercise is a hdf5-file with the same data: **ExerciseC.hdf5**
The units are the same as in page 1 of the pdf with the exercise C description. Here are some hints:

```
import h5py
f = h5py.File("ExerciseC.hdf5","r")
Pos = f["/Gas/Coordinates"][()]
Masses = f["/Gas/Masses"][()]
print("All the attributes/keys are",f.keys())
print("All the attributes/keys for the gas are",f["Gas"].keys())
f.close()
```

Read more about HDF5 in python here
`https://docs.h5py.org/en/stable/quick.html`