Solving the Photo-ionization Equation

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1 Introduction

The photo-ionization equation describes the evolution of the neutral fraction for a single cell. We will consider a simplified version of this equation, where the IGM is only composed of hydrogen and that the ionization is only due to the quasar. Then, the equation we will be solving is:

$$\frac{dx_{\rm HI}}{dt} = -\Gamma x_{\rm HI} + \alpha(T) n_e x_{\rm HI}$$

where $\alpha(T)$ is the recombination rate:

$$\begin{aligned}\alpha(T) = \exp(&-28.6130338 - 0.72411256\ln(T) - 2.02604473\times10^{-2}\ln(T)^2 - 2.38086188\times10^{-3}\ln(T)^3 \\ &- 3.21260521\times10^{-4}\ln(T)^4 - 1.42150291\times10^{-5}\ln(T)^5 + 4.98910892\times10^{-6}\ln(T)^6 \\ &+ 5.75561414\times10^{-7}\ln(T)^7 - 1.85676704\times10^{-8}\ln(T)^8 - 3.07113524\times10^{-9}\ln(T)^9)\end{aligned}$$

Γ is the ionization rate due to the quasar and is given by:

$$\Gamma = \int_{\nu_0}^{\infty} \frac{L}{4\pi r^2 h\nu}\sigma(\nu)d\nu$$

where ν_0 is the minimum frequency of light that can ionize hydrogen and $\sigma(\nu)$ is the photo-ionization cross section and is given by[1]:

$$\sigma(\nu) = 6.30\times10^{-18}[1.34(\nu/\nu_0)^{-2.99} - 0.34(\nu/\nu_0)^{-3.99}]$$

2 Methods

First, we will solve the photo-ionization equation for a single cell at some arbitrary location from a quasar. In this case, we will consider that the quasar behaves like a 'lightbulb', i.e it has a constant light curve. Then, we will do the same in the case that the quasar is flickering, i.e the light curve and therefore Γ is periodic.
Lastly, we will solve the photo-ionization equation for some sight-lines using the 1D Radiative Transfer (1DRT) code developed and introduced in [Chen & Gnedin(2021)].

[1]Equations were taken from [Bolton & Haehnelt(2007)]

3 Results

3.1 Lightbulb model

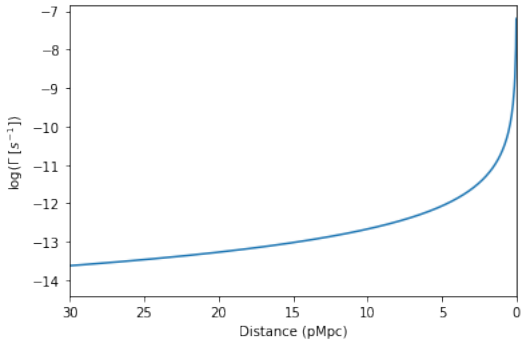


Figure 1: Here, we plot the logarithm of Γ along a single line of sight from a randomly chosen quasar in the CROC simulation.

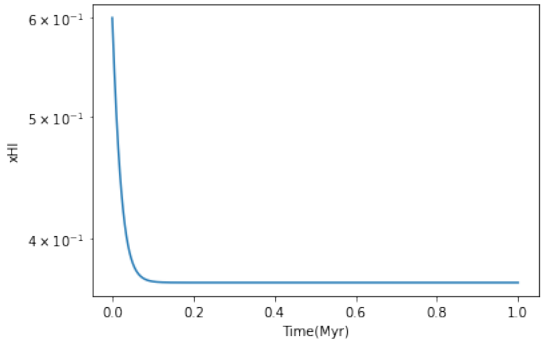
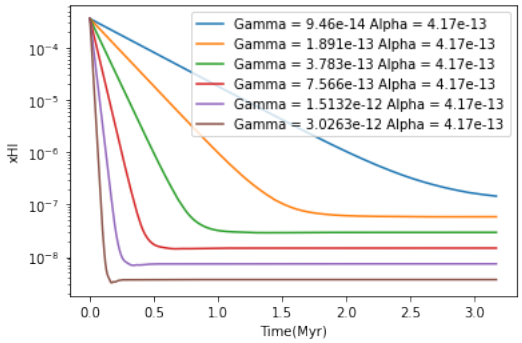


Figure 2: This is a plot of the neutral fraction for a single year over a period of 1 Myr. Here, we assume that the cell is isolated, i.e that all the cells between this and the quasar are transparent to all EM radiation. This plot was also produced assuming that the quasar is a 'lightbulb', i.e it has a constant light-curve.



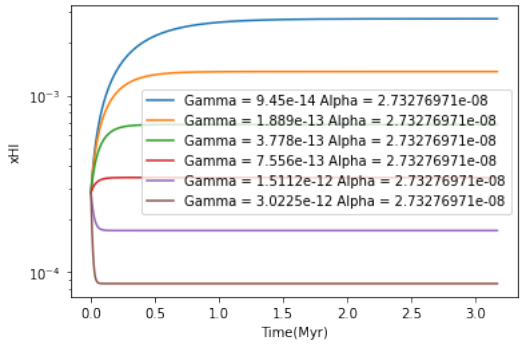
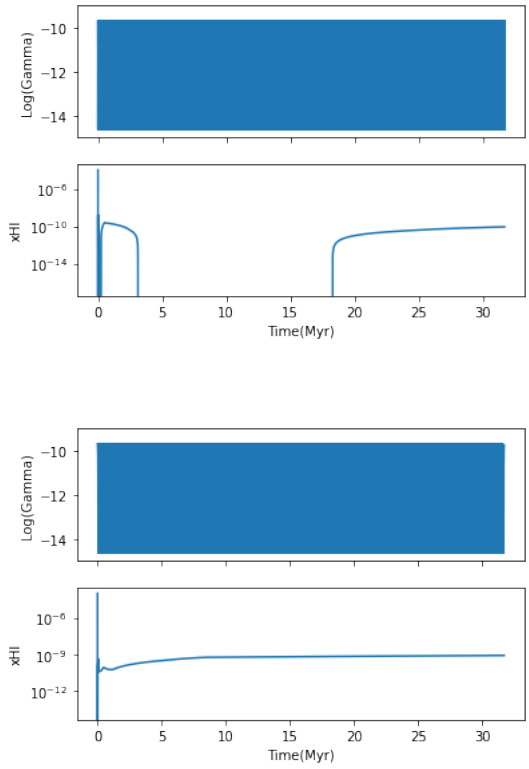


Figure 3: The above two plots illustrate the evolution of the neutral fraction of an isolated cell for some different values of Γ and α.

3.2 Flickering Quasars



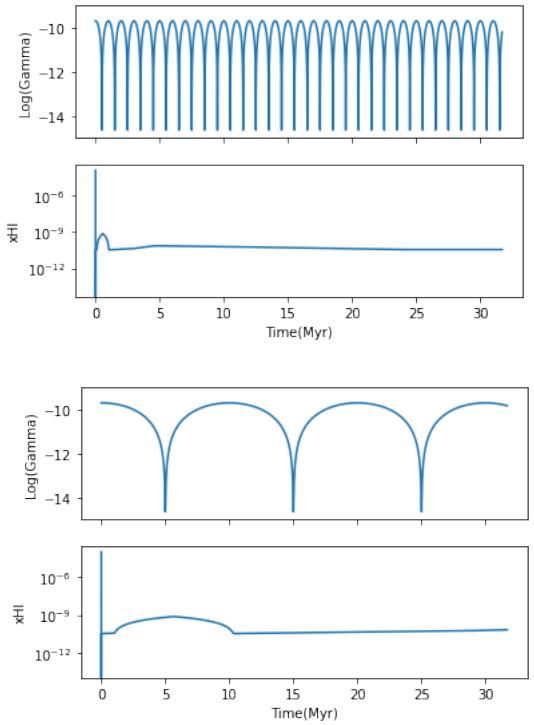
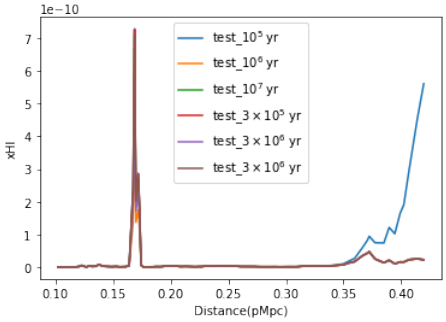


Figure 4: The above shows various periodic Γ functions that were used to solve the photo-ioniztion equations. All the functions had the same amplitude, with periods of 0.01, 0.1, 1, 10 Myr respectively.

3.3 1D Radiative Transfer



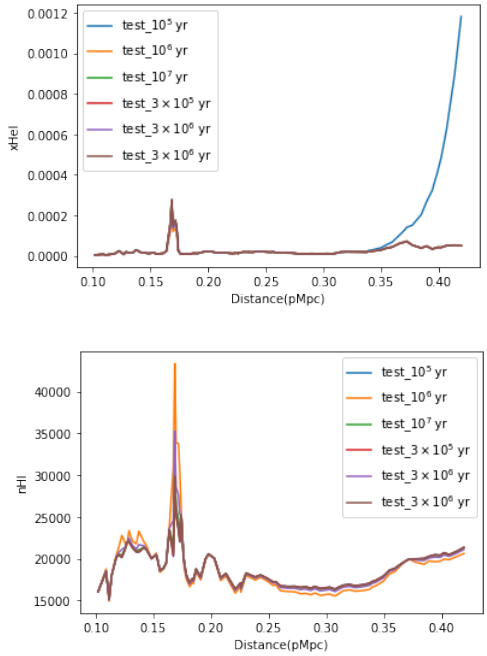


Figure 5: Here, we plot the neutral hydrogen fraction, the neutral helium fraction and the neutral hydrogen number density for a particular sight line from a quasar using 1D radiative transfer code.

References

[Bolton & Haehnelt(2007)] Bolton, J. S., & Haehnelt, M. G. 2007, Monthly Notices of the Royal Astronomical Society, 374, 493, doi: http://doi.org/10.1111/j.1365-2966.2006.11176.x10.1111/j.1365-2966.2006.11176.x

[Chen & Gnedin(2021)] Chen, H., & Gnedin, N. Y. 2021, The Astrophysical Journal, 911, 60, doi: http://doi.org/10.3847/1538-4357/abe7e710.3847/1538-4357/abe7e7