ENERGY DISSIPATION OF ENERGETIC ELECTRONS IN THE INHOMOGENEOUS INTERGALACTIC MEDIUM DURING THE EPOCH OF REIONIZATION

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ABSTRACT

We explore a time-dependent energy dissipation of the energetic electrons in the inhomogeneous intergalactic medium (IGM) during the epoch of cosmic reionization. In addition to the atomic processes, we take into account the inverse Compton (IC) scattering of the electrons on the cosmic microwave background photons, which is the dominant channel of energy loss for electrons with energies above a few MeV. We show that: (1) the effect on the IGM has both local (atomic processes) and non-local (IC radiation) components; (2) the energy distribution between hydrogen and helium ionizations depends on the initial energy of an electron; (3) the local baryon overdensity significantly affects the fractions of energy distributed in each channel; and (4) the relativistic effect of the atomic cross-section becomes important during the epoch of cosmic reionization. We release our code as open source for further modification by the community.

Key words: cosmology: theory – dark ages, reionization, first stars – dark matter

1. INTRODUCTION

Energy dissipation of high-energy electrons and photons in the intergalactic medium (IGM) is an essential problem when accounting for the effect of dark matter (DM) annihilation on the thermal and ionization history of the universe during the epochs of recombination and reionization. Many previous studies on the topic of electron propagation in the IGM were focused on the hard radiation from quasars and a range of energies up to 10 keV. However, various theories of DM, including weakly interacting massive particles (WIMP), predict that the products of its annihilation consist of much higher-energy particles. Therefore, in this study we explore the energies above 10 keV and up to 10 GeV.

The physical processes that become important for the energy dissipation of the electrons with initial energies between 10–100 keV and 10 GeV are the inverse Compton (IC) scattering on the cosmic microwave background (CMB) photons. Also, due to large timescales, the redshifts of photons produced by the IC become a substantial energy drain.

We developed a Monte Carlo code that can account for these additional effects, along with more common ones such as collisional ionization and excitation, and Coulomb interactions. The objective of this paper is to estimate the fraction of energy injected into the IGM through different processes. A detailed study of the dissipation of the full DM annihilation spectrum after hadronization and its effect on the IGM is out of the scope of this paper.

The energy range considered in many previous studies (Shull 1979; Shull & van Steenberg 1985; Dalgarno et al. 1999; Furlanetto & Stoever 2010; Valdés et al. 2010) is below 10 keV. In these studies the distribution of energies between atomic processes (ionization, excitation, and heat) was explored. We checked our results for consistency with these studies and find reasonable agreement. Since the energy range below 10 keV is well-studied, we focus on higher energies.

In Valdés et al. (2010) the authors consider higher energies, but do not take into account time evolution and redshifting. In contrast to previous works, we avoid the instantaneous approximation, because the timescales associated with the energies we are considering can be comparable with cosmological timescales. The absorption of energetic photons on cosmological scales is well-studied in Zdziarski & Svensson (1989).

Time-dependent propagation of energetic electrons and photons during the epoch of recombination is studied in Slatyer (2015) in the context of DM annihilation. Since the universe is very uniform at high redshifts, the inhomogeneity of the IGM is neglected in that study. Here we consider lower redshifts (the epoch of reionization), when halos are already formed, and most of the DM annihilation happens within them. Therefore, it is important to consider the inhomogeneity and local overdensity.

2. PHYSICAL PROCESSES

Our Monte Carlo code starts with an electron (photon) of a given energy. The code evaluates all possible physical processes that the particle can be apart of. These processes can be divided into discrete events and continuous processes. For the discrete events, such as collisional ionization and excitation (and photoionization for photons), the code calculates the probability of the event based on the cross-sections and randomly decides whether the particle will interact or not within the current time step. We choose the time step to be small enough that the probability of the event will be less than 1%; therefore, only one or zero discrete interactions happen at each time step. (Additionally, if a secondary particle is formed, i.e., after collisional ionization, the code evaluates its initial energy, and then propagates it independently from other particles with an individual choice of a time step.)

The continuous processes include electrons’ deceleration in the plasma and IC scattering. While these processes are in fact also quantized, we can assume them to be continuous compared to the collisional ionization and excitation due to their higher frequency and lower energy losses per interaction. Therefore, the code integrates the energy losses in each channel during the time step, and then subtracts them from the electron’s energy.
A collection of theoretical results on the electron–atom collisional cross-sections is available in the convergent close-coupling (CCC) database\(^1\), and there are fits available, for instance, in Shull & van Steenberg (1985), Arnaud & Rothenflug (1985), and Stone et al. (2002). However, the fits mentioned above are valid only in a non-relativistic case. When the energy of an electron exceeds \(\sim 1.5\text{ MeV}\), the relativistic effects increase the cross-section (Kim et al. 2000). During the epoch of recombination the IC kicks in on energies much lower than \(\sim 1.5\text{ MeV}\) (see Figure 3), and therefore this correction does not play a significant role. However, during the epoch of reionization in moderately overdense regions the relativistic correction becomes noticeable (see Section 3.4).

The most important process for energy dissipation of high-energy electrons is the IC scattering on CMB photons. We account for it using the Klein–Nishima cross-section. Simultaneously with the electron losing its energy, we compute the spectrum of the IC photons. The deceleration of an electron due to interactions with charged particles is calculated with the equations for the Coulomb logarithm given in Spitzer (1962).

We use photoionization cross-sections from Verner et al. (1996). The elastic and inelastic scattering and pair production cross-sections are taken from the XCOM photon cross-section database (Berger et al. 2010). Also, we include the cosmological redshifting.

In this study we consider hydrogen and helium atoms, assuming some fixed ionization fraction. Therefore, our model is not fully self-consistent, in the sense that we neglect the effect of high-energy particles on the IGM ionization and temperature. A detailed study of the effects on the IGM ionization and temperature throughout the epochs of reionization, and their possible signatures in observations, is out of the scope of this paper.

3. RESULTS

In this paper we consider only redshift 30 as a representative moment for the epoch of reionization. At this point many DM halos are already collapsed, but the star-producing galaxies are still undergoing formation. Our conclusions hold at all redshifts below 100. At higher redshifts most of the discussed effects are insignificant due to the homogeneity of the matter distribution.

3.1. Primary Electron

We inject test electrons with various energies at redshift 30 and ambient ionization fractions: \(\text{H} \equiv 1\%\), \(\text{He} \equiv 1\%\), \(\text{He} \equiv 0\%\). The fractions of energy dissipated into the ionization and excitation of H\(_1\), He\(_1\) and He\(_\text{II}\), heat, and IC scattering are recorded as functions of time.

For the electrons with energies higher than \(\approx 1\text{ MeV}\), the IC becomes a dominant channel of energy loss. The produced spectrum of the IC photons partially lies under the hydrogen ionization threshold, and partially at very high energies where the cross-section with atoms becomes small. We discuss the propagation of photons in Section 3.2. Since a photon can easily escape the halo due to a long mean free path and relatively small halo sizes at redshift 30, we assume zero overdensity and a neutral medium while calculating the photon propagation. In reality, things like the topology of the ionized regions and overdensities might play a significant role.

\(^1\) http://atom.curtin.edu.au/CCC-WWW/

Therefore, with this method we can only estimate the upper limit of effectiveness.

With the IC photon spectrum, we can subdivide it into three components. First, there are low-energy photons that do not interact with the IGM. Second, there are the “effective” photons that will interact with the IGM through photoionization, inelastic collisions, or pair production. Lastly, there are the photons that are so energetic that they will not interact with the IGM until redshift 0. In Figure 1 the total fractions of energies deposited into the atomic processes, the IC photons, and the “effective” IC photons, are shown.

Changing the ambient ionization fraction will not affect the IC scattering rate (since it depends only on the energy density of CMB photons). The dependence on the ionization fraction of all other processes was well-studied in Furlanetto & Stoever (2010) and Shull & van Steenberg (1985). Therefore, we leave them out scope of this paper.

The redshift changes the energy of the transition to the IC regime, but qualitatively the picture remains the same. The rate of IC scattering is proportional to the energy density of photons, therefore it scales as \((1 + z)^2\), while atomic processes scale only with the density as \((1 + z)^3\).

The parameter that might be the most important, especially in the context of the DM annihilation during the epoch of reionization, is the local baryon overdensity. We increase it to 100 and 1000, while keeping all other parameters fixed. In Figure 2 the total fraction of energy that can be potentially absorbed by the IGM is plotted for different local baryon overdensities. The rate of atomic processes increases proportionally to the density, while the density of CMB photons and therefore the rate of IC scattering remains unchanged. It leads to the increase of the transition energy threshold between atomic processes and IC scattering. Consequently, the fraction
of IC photons decreases, followed by the decrease of “effective” photons.

In Figure 3 we show the energy of the electrons at which they distribute half of their energies into the IC photons and half into the atomic processes. It shows that in any cosmological environment the IC scattering is significant only for extremely high-energy electrons. For instance, the IC scattering is not important for the electrons produced by X-rays emitted by hard sources like quasars.

The spatial scale for the electron energy dissipation is limited by the fact that the ionization cross-section does not go below $10^{-19}$ cm$^{-2}$ for all energies (Kim et al. 2000). Considering $z \approx 30$ and the ionizing fraction does not exceed 10%, the mean free path is of the order of $\sim 500$ pc. This is close to the galactic scales; however, the galaxies have not yet been formed at such high redshifts. Therefore, we assume the energy dissipation of an electron to be local. In order to properly calculate the propagation of the charged particles in galaxies, particularly in the Milky Way, one has to make assumptions regarding the gas distribution within the disk. A detailed study of the Milky Way is carried out in Buch et al. (2015).

Also, the timescale at all redshifts (from 0 to 1000 s) is smaller than the Hubble time (Furlanetto & Stoever 2010). Therefore, the energy dissipation of a prime electron can be assumed to be instantaneous and the effect on the IGM can be assumed to be local. However, the IC photons can have large mean free paths and therefore affect the IGM non-locally and with a delay. Figure 2 shows that the baryon overdensity determines whether the effect on the IGM will be local or not.

### 3.2. Primary Photon

The IC photons produced by a high-energy electron are also energetic. Therefore, we study the energy dissipation of the energetic primary photons. We inject test photons with energies up to $10^8$ eV at redshift 30. The ambient ionized fraction is assumed to be 0 to maximize the absorption rate.

In Figure 4 the energy fraction of the photons absorbed by the IGM in any process since their emission is plotted. The absorption of photons is not instantaneous, even with our assumption of a fully neutral medium. Therefore, the Figure 4 confirms that the effect of IC photons can be non-local.
3.3. Ionization of the IGM

In the context of the epoch of reionization, the most interesting channel of energy dissipation is the ionization of the IGM. The ionization efficiency of energetic electrons below 10 keV was studied in Furlanetto & Stoever (2010). Here we added the IC photons, and therefore we consider electrons with higher energies.

We use the same environment parameters as in Figure 1. In Figure 5 the energy fractions that go to hydrogen and helium ionization are plotted. Two main features can be observed.

First, the efficiency of the ionization is not uniform across the considered energy range. There is a dip at 10^6 eV that is associated with the regime where low-energy IC photons are produced, and another dip at 10^10 eV, which is associated with a regime when photons that are too high-energy are produced.

Second, the relative fraction of the energy going to helium is also not constant throughout the energy range. At energies around 10^7 eV, the helium ionization becomes almost as efficient as the hydrogen ionization. The reason for that is that the IC spectrum produced by the electrons of this energy peaks near the helium ionization threshold. At this energy the helium photoionization cross-section exceeds the hydrogen cross-section, and therefore is ionized more efficiently.

However, all these calculations are made assuming a uniform ionization fraction. In reality we expect to have ionization fronts that will complicate the calculation and that will require proper radiative transfer models.

3.4. Relativistic Correction

In Figure 6 we repeat two curves from Figure 2 for the overdensity 100, but that are calculated with and without relativistic correction. The atomic cross-sections for the relativistic case are taken from Kim et al. (2000), and those for the non-relativistic are from Arnaud & Rothenflug (1985) and Stone et al. (2002). In the chosen environment, the transition to the IC regime happens around the same energy, at which relativistic effects become important (~1.5 MeV). At lower redshifts a transition at the same energy would correspond to a lower overdensity for the reason mentioned in Section 3.1. In the energy range 10^6–10^8 eV the introduced correction can reach a factor of a few. In the other environments where the transition energy is not in the proximity of 1.5 MeV (for instance, during the epoch of recombination) this effect is negligible.

4. CONCLUSIONS

The study set out with the aim of highlighting the complexity of the energy dissipation of very high-energy electrons during the epoch of cosmic reionization. The results of this study indicate the following.

1. There are two components for energy dissipation—the atomic processes and the IC radiation (Section 3.1). The atomic processes affect the IGM locally and almost instantaneously, while the IC photons can travel for a long time before being absorbed (Section 3.2). The channel through which the majority of the energy dissipates depends on the initial electron energy. In the presence of DM halos, these two channels could affect the IGM in dramatically different ways, even if the total energy is identical. If the electrons have low energies, then all the effects are enclosed in the halos; if the energies are high enough, then the impact on the IGM can be global.

2. The ionization rates of different elements depend on the initial energy of the electron (Section 3.3). This may lead to a complicated ionization front structure, if such a structure is driven by the IC photons.

3. The local baryon overdensity affects the energy distribution between different channels (Section 3.1). This effect might play a significant role, especially when taking into
account the fact that DM and baryon overdensity fields are correlated.
4. The relativistic effect manifests itself in a specific energy range, and within that range it can reach a factor of a few. The environment in which this effect is most pronounced forms only during the epoch of reionization (Section 3.4) and is not present at the epoch of recombination.

This study shows that the energy dissipation of an energetic electron in the IGM involves many physical processes. In contrast to the epoch of recombination, accurate treatment of DM annihilation during the epoch of reionization requires taking into account both the spatial distribution of DM and baryons. However, those are not well-known at high redshifts and small scales. This is one of the key issues to consider for future studies.

The code used to perform the presented calculations is released open source as a Python module: http://kaurov.org/codes/radiator/. It may have important implications for developing more sophisticated models of DM annihilation during the epoch of cosmic reionization.

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