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Exploring Cosmic Rays Ionization Power

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Abstract. After the so-called cosmic recombination the expanding universe entered into a period of darkness, since most of the matter was in a neutral state. However, about a billion years later the intergalactic space was once again ionized. The process, known as the cosmic reionization, required the operation of mechanisms that are not well understood. Among other ionizing sources, Population III stars, mini-quasars, and X-ray emitting microquasars have been invoked. All these models relay on the ionizing power of photons. But what about charged particles?. In this contribution we quantify the ionization power of cosmic rays (electrons and protons) in the primordial intergalactic medium.

1. Introduction

Around 380000 yr after the Big Bang, the combination of protons and electrons formed neutral gas allowing the radiation to decouple from matter. The universe entered then in a “dark age", that lasted up to about a billion years (e.g., Ellis, Maartens & MacCallum 2012). How the universe was reionized is a major topic in current cosmology. The formation of the first stars of zero metallicity, at redshift $z \sim 20$, resulted in the injection of a large number of ultraviolet (UV) photons (e.g., Loeb 2010). However, it seems difficult for these photons to interact with neutral gas at large distances from the stars, given the high-column densities of the primordial star-forming clouds. Recently, Mirabel et al. (2011) have proposed that X-rays from accreting black holes in early binary systems might have played a crucial role, because of the longer mean free path with respect to the UV radiation.

The first generations of microquasars should have not only produced copious X-rays, but also relativistic particles through their jets. Moreover, unlike the X-rays from the disk that are injected in the vicinity of the star, the jets can propagate hundreds of parsecs and escape the original cloud where the star formation took place. Once the jets were in what would become into the intergalactic medium, the termination shocks can re-accelerate protons and electrons up to relativistic energies. Then, these particles would diffuse, ionizing the medium they encountered. In this contribution we offer a quantitative estimate of the ionizing power of these particles as they diffused through the early universe.

In the next section we describe the simulations of cosmic ray (CR) propagation in the early universe. Then, in Section 3 we discuss the obtained results. We close with implications of our results in Section 4.

2. Simulations

In order to estimate the ionization power of electrons and protons injected directly into the intergalactic medium (IGM) we have used a heavily modified version of the AIRES code (see AIRES Manual). AIRES is a particle cascade simulation suite originally designed to simulate particle cascades initiated by CRs on Earth's atmosphere. We have modified AIRES propagation routines to simulate the conditions of the primigineous IGM. We have added a redshift-dependent monochromatic photon field to simulate the cosmic microwave background (CMB) and a material medium of hydrogen atoms with redshift-dependent number density. We added inverse Compton scattering and $e^{\pm}$ photo-pair production for electrons, positrons and photons. Neutron decays have been also included.

When a particle cascade develops, most of the ionization in the traversed medium is produced by low energy particles, especially electrons and photons in and below the keV energy range. Unfortunately, the full simulation of all processes leading to particles in and below the keV range would require humongous amounts of CPU time. To circumvent this problem, the generation of particles below a certain threshold (100 keV for electrons and photons, and 500 keV for other particles) has not been directly simulated. Instead, the generation of low energy particles is represented by an averaged energy loss per amount of traversed matter, that has been subtracted from all charged particles during their propagation.

As low energy particles lose most of their energy through ionization, the subtracted energy has been considered to be ultimately deposited in the traversed medium through ionization. The number of ions that would have been generated by these low energy particles can then be estimated using the mean energy loss per ionization event $I_{\rm H}$. We take $I_{\rm H}$ to be ≈ 36 eV, considering that 10.2 eV goes to ionize the atom and ≈ 25.8 eV corresponds to the average kinetic energy of the outgoing electron, of which 22.3 eV are lost in exitations of atomic levels and 3.4 eV in heating of the gas (Spitzer & Tomasko 1968).

To further speed up the simulations, we have discarded particles that fell below the low energy threshold during their propagation. The energy carried away by these particles has also been considered to be ultimately deposited in the medium through ionization.

The IGM has a redshift dependence. We have adopted a density of the primordial IGM of $n_{\rm H} = 2.5 \times 10^{-30}(1+z)^3$ g cm^{-3} (e.g., Ellis et al. 2012). The CMB has been considered monoenergetic with photon energy $E_{\rm CMB} = 3.75 \times 10^{-4}(1+z)$ eV, and a photon density $u_{\rm CMB} = 0.05\,(1+z)^3$ cm^{-3}. For the magnetic field of the IGM we have taken the value $B = 10^{-17}$ G (e.g., Stacy & Bromm 2007; Loeb 2010; Bromm 2013). The model we have used for the evolution of the universe is that of the standard spatially-flat six-parameter ΛCDM cosmology, with a Hubble constant $H_0 = 67.3 \pm 1.2$ km s^{-1} Mpc^{-1} and a

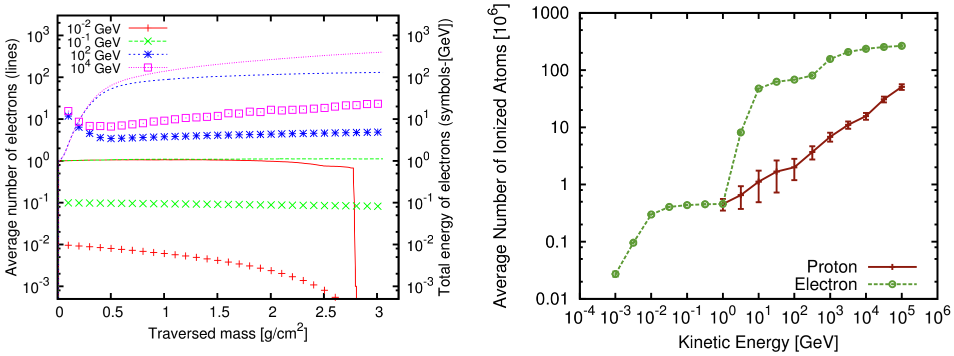

Figure 1. (left) Average longitudinal development of electrons and (right) total ionization power of particles injected in the IGM at redshift $z = 19$ and propagated through redshift $z = 5$

matter density parameter $\Omega_{\mathrm{m}} = 0.315 \pm 0.017$, in accordance with latest results from the Planck Collaboration (2014).

Under these assumptions, simulations of electrons in the 1 MeV - 100 TeV and protons in the 1 GeV - 100 TeV energy range have been generated. Particles start at redshift $z = 19$ and they are propagated through the IGM until they reach $z = 5$, the epoch at which the reionization is considered to be complete (Loeb 2010). During this lapse, particles traverse up to ~ 3.1 g cm^{-2} of matter.

3. Results

Our simulations for electrons primaries show that below the energy threshold for interactions with the CMB, - roughly 1 GeV - no particle cascades are produced. An example of the average longitudinal development of 10 MeV electrons is shown in Figure 1 (left). At these energies, electrons propagate loosing their energy mainly by ionization of the hydrogen atoms they encounter on their path.

Electrons below 10 MeV loose all their energy in the IGM before the reionization epoch ends, producing a number of ionizations (i.e. an ionization power) proportional to their initial energy. This is evidenced as a unitary slope in the low energy end of Fig. 1 (right).

Above 10 MeV, electrons survive the reionization epoch, as can be seen on the average longitudinal profile for 100 MeV electrons shown in Fig. 1 (left). This gives a plateau in the ionization power for electrons between 10 MeV and 1 GeV seen in Fig. 1 (right). The energy deposited through ionization by a single particle for a fixed amount of traversed matter has little dependency on its energy.

Once the energy of the primary electrons reach the threshold of inverse Compton with the CMB, particle cascades start being generated. The number of particles quickly rises and so does the total energy lost through ionization. At some point these particles start having enough energy to survive the reionization epoch. This gives the second plateau in Fig. 1 (right).

A second sudden but smaller rise in the ionizing power is produced when secondaries also reach the CMB interaction threshold, triggering more cascades. An example of this type of cascades is given in Fig. 1 (left) for 10 TeV electrons, where it can be seen that the number of electrons and the energy they carry continues to rise, in contrast with the 100 GeV case.

For proton primaries we started our calculations at 1 GeV. At these energies protons have a big variability in their ionization power as the 3.1 g cm^{-2} of traversed matter is well below the mean free path of $p-p$ interactions. Protons that do not interact survive the reionization epoch and deposit very little energy, giving a small ionization power. Protons that do interact generate pions that promptly decay into muons, electrons and photons that in turn generate cascades that do have a big ionization power. This yields a big variability in the ionization power of protons, specially at low energies, and a slope lower than 1 in the ionization power as can be seen in Fig. 1 (right).

4. Conclusions

Only low energy lectrons have a ionization power per unit energy comparable with UV or X-Ray photons, i.e. in the order of 20 ionizations per keV. However, microquasar jets inject particles with a power law spectrum making low energy particles dominate the microquasar total ionizing power. Furthermore, these particles would be injected directly into the IGM, bringing directly where UV photons cannot reach. The contribution from protons would be a hundred times lower, but their bigger gyroradius make them diffuse faster and deeper into the IGM.

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