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Heating of the intergalactic medium by cosmic rays in the early universe

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The intergalactic medium (IGM) we see today is hot and ionized, but the early Universe was cold and almost neutral. The transition to the ionized Universe was driven by stars and galaxies formed in the early Universe, which emitted ionizing photons. Understanding reionization history is crucial because it reflects the formation and evolution of stars and galaxies. The intermediate stage of cosmic reionization at redshift $z \sim 10$, i.e. ~ 500 Myr after the Big Bang, is particularly interesting because the IGM temperature at this epoch is expected to be revealed by future radio observations via the 21-cm line of neutral hydrogen. At this time, reionization remains patchy, while the IGM is globally heated by X-ray photons which have long mean free paths. However, in addition to X-rays, cosmic rays (CRs) can also contribute to the heating of the IGM if they are accelerated at this time.

CRs are high-energy charged particles with an energy density comparable to other components like thermal particles and magnetic fields in the local ISM. CRs are thought to play important roles in galaxies, such as driving galactic winds and penetrating and ionizing molecular clouds. Since CRs are expected to be accelerated in supernova remnants of the first stars in the same way in the present Universe [1], they can influence the evolution of galaxies and the IGM. Here we focus on IGM heating by CRs and demonstrate that the CR-driven resistive heating induced is important for IGM heating [2].

We consider the situation where CRs accelerated in a galaxy stream into the IGM. The electric current carried by the streaming CRs induces electric fields and thermal electrons are accelerated. As a result, a return current of electrons balances the CR current at steady state. However, since collisions between thermal particles are negligible on a cosmological time scale, resistive electric fields are induced to maintain the current neutrality. The energy dissipation due to the resistive electric fields increases the temperature of the IGM.

To clarify the relative importance of CR-driven resistive heating to the other heating mechanisms of the IGM, we calculated the temperature evolution of the IGM using a simple model. In our model, we assumed that CRs stream radially out of a galaxy and that the IGM has the average temperature and density at z∼10 before heating begins. We solved the evolution equations for temperature and ionization degree since the heating rates depend on them. We solved the temperature evolution by the following heating mechanisms with radiative cooling: (1) X-ray heating via photoionization, (2) direct heating by CRs via ionization and Coulomb collisions, and (3) CR-driven resistive heating. We also included the resistivity due to collisions between electrons and neutral particles, as well as that caused by Coulomb collisions between thermal charged particles.

Figure 1 displays our results. The right panel shows that the ionization degree remains almost unchanged. The red and blue lines in the left show the temperature evolution with and without CR-driven resistive heating, respectively, while all other mechanisms are included in both cases. This figure shows that for the parameters used, resistive heating is the most dominant heating mechanism, even over X-ray heating, which is accepted as the standard heating mechanism in the literature. Since the spatial patterns of CR and X-ray heating are expected to be different, the signature of CR heating can be obtained by future radio observations of the 21-cm line power spectrum with the SKA [3].

References

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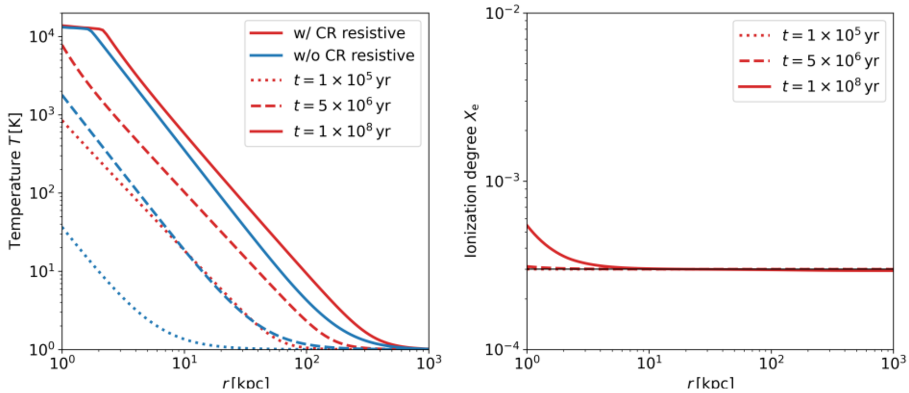

Figure 1 Time evolution of the IGM temperature (left) and ionization degree (right) as a function of distance from a galaxy. The CR resistive heating is included for the red lines.