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Cosmic-ray Driven Resistive Heating of the Intergalactic Medium in the Early Universe and Its Implications for 21-cm Line Observations

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In the current Universe, cosmic rays (CRs) are believed to influence the baryonic cycle of galaxies. Because of their high energy, CRs can penetrate dense molecular clouds, where ultraviolet photons cannot reach, and ionize the gas, thereby regulating the star formation process. In addition, the energy density of CRs in the local interstellar medium is comparable to that of the other components, including thermal particles, turbulence, and magnetic fields. Because of this, CRs exert significant pressure on the interstellar gas and help drive galactic winds. However, the understanding of their influence on galaxies and the intergalactic medium (IGM) in the early universe is very limited. In this study, we discuss the ionization and heating of the IGM by CRs in the early universe, as a possible impact of CRs.

Before the completion of cosmic reionization, which occurred at redshift $z \sim 6$ ($t \sim 1\,\mathrm{Gyr}$ after the Big Bang), the temperature of the IGM can be inferred from observations of the 21-cm line of neutral hydrogen, which appears by emission or absorption against the cosmic microwave background, depending on the temperature. Since the line is redshifted according to the distance of the emitter or absorber to the observer, the thermal history of the IGM can be obtained by observing the 21-cm line. Although observations of the 21-cm line from epoch of reionization are currently limited, it is expected that future radio observatories, such as Square Kilometer Array (SKA), make it possible to observe them[1]. To extract cosmological and astrophysical information that will be obtained by near-future observations, it is important to understand how the IGM temperature evolves over time.

In our previous study[2], we proposed that streaming CRs, accelerated in galaxies in the early universe, and escaping out of them, drive resistive heating in the IGM. In this mechanism, a return current of thermal electrons is induced by streaming CRs to maintain current neutrality, and collisions between the electrons responsible for the return current and thermal protons mediate the resistivity. We showed that this mechanism can dominate the determination of the IGM temperature in the early universe at $z \sim 10$ ($t \sim 500\,\mathrm{Myr}$), surpassing X-rays, which are conventionally considered the main contributors to IGM heating during this epoch.

In this study, we update that work by incorporating the evolution of the ionization degree and all the relevant processes determining the ionization degree and temperature of the IGM. Figure 1 shows the temperature (left panel) and ionization degree (right panel) of the IGM as functions of distance from a galaxy. The black solid lines show the temperature and ionization degree when we include CR-driven resistive heating, while the green lines show those when we only consider X-rays as heating sources. This figure clearly shows that the IGM temperature increases and the heated region is extends when resistive heating is considered. In addition, we discuss how different heating scenarios can be distinguished by future observations of the 21-cm line.

References

[1] L. Koopmans et al., Proc. Sci., Vol. 215, Advancing Astrophysics with the Square Kilometre Array (AASKA14). SISSA, Trieste, PoS#001 (2015)
[2] S. L. Yokoyama and Y. Ohira, MNRAS, **523**, 3671 (2023)

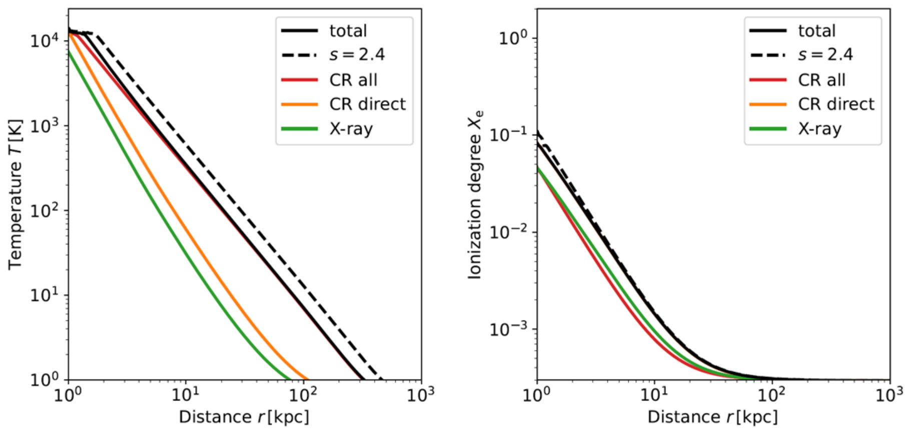

Figure 1 The temperature (left) and ionization degree (right) of the IGM as functions of distance from a galaxy. The CR resistive heating is considered in black and red lines.