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Can Cosmic Rays Heat the Intergalactic Medium?

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We consider the effects of cosmic ray (CR) protons generated in the early star forming galaxies, on the thermal history of the intergalactic medium (IGM). CRs are assumed to be created in supernovae (SNe) explosions and are typically confined in the collapsed objects for a short period before escaping into the IGM. Galactic outflows can facilitate this escape by advecting CRs into the IGM. An outflow that results in a termination shock can also generate more CRs. We compute the global star formation rate density hence the SNe rate using the Press-Schechter formalism in the context of a canonical ΛCDM model. We show that the heating due to CR protons from the above processes, can compensate for adiabatic cooling and explain the measured IGM temperature at redshifts $z \sim 2 - 4$, even with early reionization.

1. Introduction

Cosmic rays are thought to be generated and accelerated from the shocks created by the exploding supernovae in the star forming regions, termination shocks created by outflows from galaxies and accretion shocks during structure formation. The properties of CRs in our Galaxy is well documented [1, 2, 3, 4]. The energy density in the proton component is about 1 eV cm^{-3}, and CRs are thought to be confined to the Galactic disk for about 10^7 yr before escaping, presumably into the IGM. It is widely accepted that $\geq 15\%$ of the average SNe energy must go into accelerating the CRs so that the flux density of CRs can be maintained at the observed value [4]. Low energy CR protons play an important role in the ionization and thermal state of the gas in the interstellar medium (ISM) of normal galaxies. The possibility that they could also play an important role in determining the thermal history of the IGM has been considered sporadically in the literature [5, 6].

The temperature of the low density intergalactic medium is believed to retain some memory of the reionization process [7]. Analysis of Lyα absorption spectra in the framework of hydrodynamical simulations and semi-analytic models [8] suggest that, the mean temperature of the IGM is in the range $10^4 \leq T(\mathrm{K}) \leq 3 \times 10^4$ for $2 \leq z \leq 4$. This has been used to argue that hydrogen reionization occurred below $z \simeq 9$ [9]. Had the reionization occurred at higher z, adiabatic cooling would have brought the temperature much below the measured value at $z = 4$. The detection of a strong Gunn-Peterson trough and the sizes of ionized regions around the highest z QSOs [10], are consistent with a large neutral hydrogen fraction at $z \simeq 6$. The CMB data from the WMAP satellite [11], however, points to an earlier epoch of reionization in the range $11 < z < 30$. Thus either new heating sources (other than photo-heating) or multiple episodes of reionization with heating at low z provided by, say, the He II reionization induced by QSOs [12], are needed to explain the IGM temperature at $z \sim 2 - 4$. Here, we consider the effect of cosmic ray protons on the thermal history of the IGM in the framework of a standard flat ΛCDM model ($\Omega_m = 0.27$, $\Omega_b = 0.04$ and $H_0 = 70$ km s^{-1} Mpc^{-1}). It is particularly timely to re-examine this issue because of the existence of good observational constraints on (i) the global star formation rate (SFR) density as a function of z (ii) epoch of reionization and (iii) temperature of the IGM.

2. Analytical formalism

Consider CR protons produced from the SNe explosions. To compute the rate of energy injected into CR protons from early star forming galaxies, one needs to know the SFR and the number of SNe explosions, f_{SN}, per solar mass of forming stars. The global comoving SFR density, $R(z)$, is observationally constrained for $z \lesssim 10$. To model the $R(z)$ we use Press-Schechter (PS) formalism as described in [13, 14, 15]. The comoving number density of collapsed objects in the mass range between M and $M + dM$ which are formed at the redshift interval $(z_c, z_c + dz_c)$ and observed at z is

$$N(M,z,z_c)dM\,dz_c = N_M(z_c)\left[\frac{\delta_c}{D(z)\sigma(M)}\right]^2 \frac{\dot{D}(z_c)}{D(z_c)}\frac{D(z_c)}{D(z)}\frac{dz_c}{H(z_c)(1+z_c)}dM\ . \tag{1}$$

The over dots represent the time derivatives. The Press-Schechter mass function $N_M(z_c)dM$ is the comoving number density of the collapse object having mass in the range $(M, M + dM)$ at redshift z_c. The critical over density of an object to collapse is δ_c which is equal to 1.686. The Hubble parameter at z is $H(z)$ and $D(z)$ is the growth factor. The rms mass fluctuation $\sigma(M)$ is normalized at $\sigma_8 = 0.84$. The lower mass cut off of halos which can host the star formation depends on cooling efficiency of the baryonic gas. Cooling due to hydrogen alone is inefficient below a temperature of 10^4K. Therefore, we will assume that halos of virial temperature $\geq 10^4$ K can host the star formation at any redshift. This gives a conservative lower limit on $R(z)$.

The SFR in a halo will depends on mass of the halo and also the elapsed time after it collapsed. For a halo of mass M which has formed at z_c, the SFR is given by [16, 15]

$$\dot{M}_{SF}(M,z,z_c) = \epsilon_{SF}\left(\frac{\Omega_b}{\Omega_m}M\right)\frac{t(z)-t(z_c)}{t^2_{\rm dyn}}\exp\left[-\frac{t(z)-t(z_c)}{t_{\rm dyn}}\right] \tag{2}$$

where ϵ_{SF} and $t(z) - t(z_c)$ are stars formation efficiency and the age of the collapsed halo respectively. It is assumed that the star formation in the halo is sustained upto a dynamical time $t_{\rm dyn} = \sqrt{\frac{3\pi}{32G\rho}}$ where ρ is 200 times the background density at z_c. The value of ϵ_{SF} is obtained by fitting the observed global SFR [17] for $z \lesssim 10$. Note that we have multiplied the observed value by a factor 7 to correct the effect of dust reddening [18]. We then have

$$R(z) = \int_z^{\infty} dz_c \int_M^{M_{\rm u}} dM'\ \dot{M}_{SF}(M',z,z_c) \times N(M',z,z_c) \tag{3}$$

Here the upper mass limit ($M_{\rm u}$) is taken to be $10^{12}M_\odot$. Further, using the "Starburst99" code [19] we get $f_{SN} = 8 \times 10^{-3}$ for Salpeter IMF (with M_{min} = 0.1 $M_\odot$, M_{max} = 100 $M_\odot$) and $f_{SN} = 1.7 \times 10^{-2}$ for a top-hat mass function with M_{min} = 40 $M_\odot$, M_{max} = 100 $M_\odot$ (denoted as "top-heavy"). We assume that the energy released from a single SNe is 10^{51}erg and a fraction $\epsilon = 0.15$ of this is utilized for accelerating the CR protons. The average rate of energy injected in the CR protons is then,

$$\dot{E}_{CR}(z) = 10^{-30}\epsilon\ R\ f_{SN}(1+z)^3\ {\rm erg\ s^{-1}\ cm^{-3}}. \tag{4}$$

The energy in the cosmic rays is distributed as a power law in momentum space. CRs propagate first within the high redshift star forming galaxy and then into the IGM. Within the galaxy CRs are assumed to loose energy mainly due to collision with free electrons as the ISM is already highly ionized by the UV photons from the stars. The escape of the CRs from the star forming galaxies will depend on the structure and strength of its magnetic field, the gas density and outflows etc. Fresh CRs can also be generated from termination shocks. Depending on all these parameters the spectra gets modified in different ways. The number of CR protons

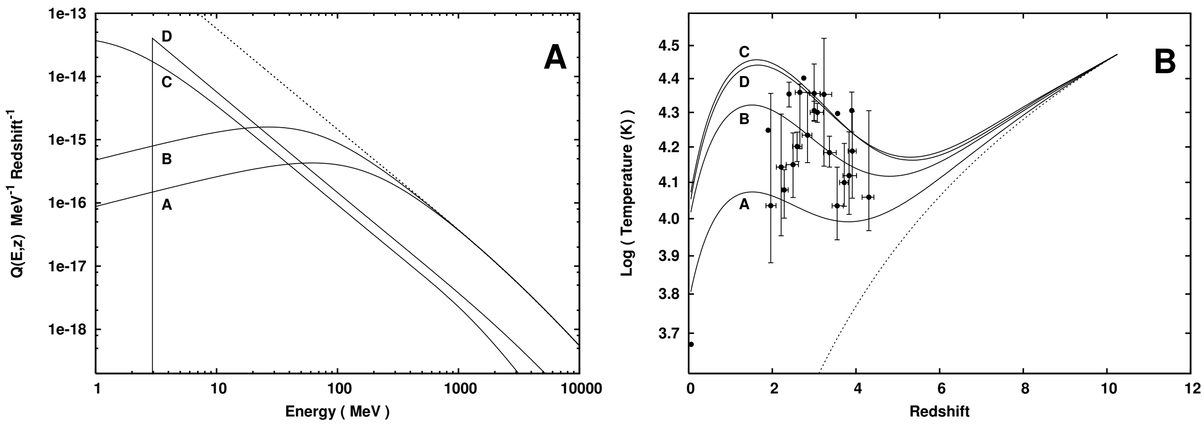

Figure 1. A. Cosmic rays spectrum originating from SNe (dotted one) and the modified spectra (solid lines) escaping from galaxy. This spectrum gets modified like the curve A and B if the CRs traverse through a grammage of $x = 10$ and 3 g cm^{-2} in the ISM respectively. Further the spectrum can get modified by the advecting wind produced by the SNe. The curve C is for the advection model, where the spectrum A has been modified by decreasing the momentum of each CR particle by a factor 10. Curve D is the CR spectrum originating from the termination shock with a sharp cut-off at 3 MeV and assuming 1.5% of SNe energy goes into CRs. For illustrative purpose the injected $Q(E, z)$ is normalized using R at $z = 15$.
B. Predicted temperature evolution of the IGM for different injected spectra given in the left panel. We follow the labeling convention as in left panel. Temperature evolution for the adiabatic cooling is shown with a dotted curve. The data points are a compendium of observations presented in [8].

$(Q(E, z)dE\,dz)$ in an energy interval $(E, E + dE)$, injected in the redshift interval $(z, z + dz)$ emerging from the star forming regions, for different scenarios, are shown in left panel of Fig 1. After escaping into the IGM, we have assumed that CRs propagate freely and transfer their energy to the free electrons by Coulomb interaction. In this process the IGM gets heated. Since the thermal history and ionization history are coupled together, we have also assume a very simple reionization model to calculate the ionization state of the IGM and assume that at redshift of reionization the IGM reached an uniform temperature of 3×10^4 K. We assume "top-heavy" IMF prior to the epoch of reionization and "Salpeter" IMF after that. Using the $R(z)$ as obtained from PS formalism and an escape fraction of 0.1 for ionizing photons we obtain the reionization redshift $z_{\rm r} \sim 10$. For details of these calculations using a simple fit for $R(z)$, and more elaborate discussion see [20].

3. Results and Discussion

The temperature evolution of the IGM for different injected spectra (as shown in Fig. 1 A) are shown in Fig. 1 B. The temperature of the IGM goes well below the observed range due to adiabatic cooling in the absence of heating sources (dotted curve in Fig. 1 B). However for all the models, CR heating leads to, $T \geq 10^4$K in the redshift range $2 \leq z \leq 4$. The average grammage traversed by the CRs in the high z star forming galaxies has to be less than 10 g cm^{-2} seen in the Galaxy, in order to produce the observed mean IGM temperature (curves A and B in Fig. 1 B). A lower grammage is reasonable for the high z galaxies, as $R(z)$ is expected to be dominated by smaller mass objects that may also be 'magnetically' younger and will confine CRs for a smaller period. These models predict cosmic ray energy density $U_{cr} \sim 6 \times 10^{-3}$ eV cm^{-3} at $z = 0$. Models with adiabatic losses or termination shocks produce higher temperatures, as they efficiently inject lower energy CRs into the IGM. At the same time they lead to overall lower cosmic ray energy densities of the order 1.5×10^{-4} eV cm^{-3} and 5.7×10^{-4} eV cm^{-3} for advecting and termination shock model respectively at $z = 0$. Models of shock acceleration [4] predict ϵ as high as $0.3 - 0.4$. In such a case even a model with grammage as seen in our galaxy will produce higher temperatures than the observed mean. Simulations of pregalactic outflows [21], find up to 30% of the supernovae energy can go into winds where as we have taken only 10%. The resulting temperature in this case can thus be much higher. The major uncertainties are related to the extent to which the IGM is magnetized and confinement issues.

4. Conclusion

We have explored the influence of CRs escaping from the early star forming regions on the thermal history of the IGM. Using a SFR density obtained from PS formalism and constrained by observations, the observed temperature of the IGM at $2 \leq z \leq 4$ can be explained as due to the CR heating, even if the epoch of reionization is as early as $z = 10$. This implies that low energy CRs in the IGM can erase the thermal memory of reionization. In conclusion, cosmic rays do provide an important source for heating the intergalactic medium, that can explain the measured IGM temperatures at high redshifts.

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