THERMAL HISTORY OF INTER-CLUSTER RELATIVISTIC ELECTRON GAS HEATED BY QUASARS

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Abstract. The thermal evolution of an inter-cluster gas of relativistic electrons heated by quasars with redshifts up to \( z = 3 \) and 4 is studied in the framework of a Friedmann—Robertson—Walker universe. The gas cools by Compton scattering with the microwave background radiation and by adiabatic cooling due to the universe expansion. Power and exponential laws of cosmological evolution of the comoving density of sources are considered. The obtained temperatures are sensitive to the form of these laws and to the heating epochs. Compared to the nonrelativistic models, the results obtained in the case of the power law present strong differences. These differences decrease when the exponential law is considered. Thermalization times are compared to the characteristic times of variation of the universe energy density and to the time-scales of energy loss by bremsstrahlung radiation and by Compton scattering. It is shown that, in some cases, nonequilibrium effects may be important. The time delay effects in the propagation of electromagnetic waves in cosmic plasma are shown to be very important for the analysis of theoretical models.

1. Introduction

The existence of an inter-cluster medium (ICM) is an open question today. This medium likely consists of primeval H and He that did not participate in galaxy formation. If the present epoch density parameter of the universe is \( \Omega_0 \approx 1.0 \) (Loh and Spillar, 1986), with a galaxy contribution of \( \approx 0.05 \), it is possible that one of the main contributions to the value of \( \Omega_0 \) comes from ICM. Many attempts have been made to detect the presence of such a medium (Silk, 1981).

The failure in early attempts for detection of the 21 cm emission and absorption lines of H\( \text{I} \) and of the Ly\( \alpha \) absorption line in the quasar spectrum led to the conclusion that if ICM exists, it would have the form of a highly ionized gas (for a good review see Weinberg, 1972; Field, 1972, 1980). A strong evidence pointing in this direction is the diffuse X-ray background (XRB) radiation in the 3–300 keV energy range. Although there are doubts about the origin of this radiation, since it can be due to discrete unresolved sources (Giacconi \textit{et al.}, 1979; Giacconi, 1987; Setti, 1987), its high degree of isotropy indicates that it can also be due to the ICM. The observed XRB has been interpreted as a thermal bremsstrahlung radiation provided by an inter-cluster plasma with a temperature of the order of 10^8 K (Cowsik and Kobetich, 1972). In this case, one has to find the heating mechanism that causes such high temperature.

Many astrophysicists have tried to explain why the ICM is ionized and have considered many heating mechanisms and studied the distortions of the cosmic microwave background radiation due to the interaction of this radiation with the ICM (Weymann, 1966; Scherman, 1979; Wright, 1979; Ikeuchi and Ostriker, 1986). The heating of the ICM by discrete sources has been early considered by Ginzburg and Ozernoy (1966).
They have studied the thermal evolution of ICM heated by galactic explosions, but did
not consider the cosmological evolution of the number density of sources. Rees (1969)
suggested that quasars could have ionized the ICM up to the redshift $z = 2$ and 3.
Aarons and Weingert (1972) studied the photoionization of intergalactic H by QSOs
taking into account the expansion of the universe as well as the cosmological evolution
of the luminosity function of QSOs and concluded that photoionizing radiation is
compatible with a universal medium with $T \approx 10^4$ K and $n \approx 3 \times 10^{-7}$ cm$^{-3}$. Such a
medium would be difficult to detect with the techniques available at the time of their
work.

Field and Perrenod (1977) have considered the heating of ICM by exploding galaxies
at a redshift $z = 3$ assuming that the comoving density of sources scales with $(1 + z)^6$.
In their model (hereafter called FP) they assume that ICM is a completely ionized gas
of H with 10% of He, in number. They fitted the XRB spectrum in the 1–100 keV energy
range for a nonrelativistic thermal bremsstrahlung radiation mechanism and found for
the present epoch temperature of the ICM and for the contribution of this medium to
the density parameter, respectively, the values $4.4 \times 10^8$ K and 0.46. On the other hand,
this model predicts high input energy rates to the gas of the order of $10^{49}$ ergs s$^{-1}$ per
source. As the average total radiated power (optical + ultraviolet + infrared) of known
quasars with redshifts up to $z \approx 2.5$ was about $10^{45}$ ergs s$^{-1}$, the validity of this model
seems to be unlikely. We know that there are today quasars with optical luminosities
up to $5 \times 10^{48}$ ergs s$^{-1}$, such as the quasar S5 0014–81 (Kühr et al., 1983), and with
X-ray luminosities up to $10^{47}$ ergs s$^{-1}$ (Sapre and Mishra, 1985), so that the quasar
heating model can be considered as realistic.

Barcons and Lapiedra (1985) studied a model (hereafter referred to as BL) of an
intergalactic plasma (IGP) of relativistic electrons in a static neutralizing ion
background. They obtained the variation of temperature with redshift taking into
account only the effect of the adiabatic cooling due to the universe expansion. The
thermal evolution of the gas in their model shows a strong difference with respect to
nonrelativistic models. The electron gas is taken as an ideal gas in equilibrium, but they
have pointed out that this is an approximation and that nonequilibrium effects could
be important. Barcons and Lapiedra have also considered the effect of time delay in the
propagation of electromagnetic waves in a plasma in a way to determine the charac-
teristics of the IGP. Barcons (1987) used the BL model to fit the XRB spectrum in the
3–300 keV energy range, taking into account relativistic corrections to electron-electron
as well as to electron-proton bremsstrahlung, and obtained $T_0 \approx 3 \times 10^8$ K and
$\Omega_{\text{IGP}} = 0.36$ for $z_m = 2$ and $\Omega_{\text{IGP}} = 0.21$ for $z_m = 4$, where $z_m$ is the maximum redshift
for the emissivity of the IGP.

Guilbert and Fabian (1986) examined the case of a plasma consisting of electrons and
protons in thermal equilibrium including relativistic corrections for the gas emissivity,
thermodynamics and Compton scattering with the microwave background radiation.
The gas with moderately relativistic temperature cools by adiabatic expansion and by
Compton cooling. They fitted the XRB with $z < 6$ and found $T_e = (1.3–2.9) \times 10^8$ K
and $\Omega_{\text{IGP}} \approx 0.25–0.3$. 