Mon. Not. R. Astron. Soc. **260,** 908–914 (1993)

Physical conditions in the intergalactic medium

Ravi Subrahmanyan★ and Lakshmi Saripalli
Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 2121, Australia

Accepted 1992 August 17. Received 1992 July 20; in original form 1992 April 27

ABSTRACT

Measurements of the spectrum of the cosmic microwave background radiation by *COBE* (Cosmic Background Explorer) limit the line integral of the electron pressure in intergalactic gas out to cosmological distances. The internal physical properties of diffuse bridges in the lobes of giant radio galaxies are also expected to reflect directly the pressure in this intergalactic medium that forms the environment of the radio structure. Surprisingly, the *COBE* limits rule out an intergalactic medium with the pressure indicated by the radio structures. This suggests that these regions are not thermally confined. However, an intergalactic medium composed of a mixture of hot nuclei and cold electrons which are not in thermal equilibrium is allowed by the *COBE* constraints, and processes during galaxy formation could provide a natural cause for an intergalactic medium with an energy density of the value indicated by the observed radio structures.

Key words: plasmas – galaxies: active – intergalactic medium – galaxies: jets – cosmic microwave background – radio continuum: galaxies.

1 INTRODUCTION

The cosmic microwave background radiation (CMB) is believed to be a relict of the 'big bang' that has propagated essentially unscattered since the recombination era. In the primeval Universe (redshift $z > 10^6$), standard cosmology expects the radiation spectrum to have a Planck form. Radiant energy release at epochs before $z \sim 3 \times 10^4$ is expected to modify the spectrum. But in the post-recombination era, processes that scatter the radiation and thereby maintain an equilibrium photon energy distribution become slow, and so energetic interactions between the relict radiation and matter will result in spectral distortions in the CMB. Specifically, any hot intergalactic gas will inverse Compton scatter the relict photons to higher energies and thereby reveal their presence as a departure of the CMB spectrum from equilibrium form. The basic theory of the interaction of CMB photons with thermal gas and the consequent distortion in the CMB spectrum has been described by Zeldovich & Sunyaev (1969). The magnitude of the distortion is quantified in terms of the 'Compton-scattering y-parameter', which is the product of the fractional energy change expected at each scattering and the mean number of scatterings that a CMB photon experiences. For a non-relativistic plasma, this 'y-parameter' is directly proportional to the integral of the electron pressure along the line of sight. Therefore, observational limits on CMB spectral distortions directly limit the electron pressure in any hot intergalactic medium (IGM).

The relativistic plasma that emerges from active galactic nuclei (AGN) in the form of jets is often observed to produce spectacular lobes of radio-emitting material that are well removed from the parent galaxy. Especially in the case of the giant radio sources, the lobes are located well outside the gaseous haloes of the parent galaxy and are therefore interacting directly with, and probing, any intergalactic material. The very existence of 'visible' hotspots at the extremities of double radio sources indicates interactions with a working surface. The ejecta from the AGN encounter resistance to their propagation, implying that an IGM exists. The advancing hotspots are probably confined by ram pressure of the IGM. But the more tenuous material, outside the jets, that forms the bridge between the nucleus and the radio lobes is expected to have expanded and attained an equilibrium state (Begelman, Blandford & Rees 1984 and references therein) in which the energy density is in equipartition between the magnetic field and particles, and where the pressure of the relativistic plasma equals the pressure of the gaseous environment. Consequently, making inferences about the physical conditions in the diffuse bridges of large-sized double radio sources is an independent means of probing the pressure of the IGM.

The absence of broad Lyα absorption troughs in the spectra of distant QSOs has been used to derive upper limits

★On leave from the Tata Institute of Fundamental Research, Bombay, India.

to the density of neutral hydrogen in any IGM (Gunn & Peterson 1965). The most stringent limits to date have been placed by Steidel & Sargent (1987), who infer that $n_{\mathrm{H\,I}}(z=0.0) < 8.5 \times 10^{-14}\, h_{50}\, \mathrm{cm}^{-3}$, assuming an Einstein–de Sitter cosmology (h_{50} denotes the Hubble constant in units of 50 km s^{-1} Mpc^{-1}). Since this value is 10^{-8} of closure density, any IGM is inferred to be highly ionized with no significant neutral gas.

The observational limits on CMB spectral distortions directly constrain the pressure in the ionized intergalactic gas that forms the confining gaseous environment of the radio galactic lobes. In the following sections, we develop this constraint to understand the implications for the nature of the IGM.

2 THE ENVIRONMENT OF RADIO GALAXIES

Giant elliptical galaxies are the hosts for most classical double radio sources, and hot gaseous coronae are commonly observed in these early-type galaxies with extents up to 100 h_{50}^{-1} kpc (Forman, Jones & Tucker 1985). It is hypothesized that the gas is the accumulation of mass loss due to the evolution of stellar systems in the galaxy and is distinct from any primordial IGM.

Miller et al. (1985) compared the internal pressures in the lobes of a sample of Fanaroff & Riley class II (FR II; Fanaroff & Riley 1974) radio sources, that have maximum extents 300–600 h_{50}^{-1} kpc, with upper limits on the external gas pressure that were derived from X-ray observations. Most parts of the lobes were found to have internal pressures exceeding the surrounding medium. However, it was possible that the bridges located at distances $<100\, h_{50}^{-1}$ kpc from the central engine, and with internal pressures estimated to be about 10^{-12} dyn cm^{-2}, were statically confined. More diffuse and extended X-ray emitting gas is observed associated with the potential wells of clusters of galaxies (Sarazin 1986). Cyg A is embedded in intracluster gas and Arnaud et al. (1984) claimed that the lowest value of internal pressure within the lobes (about 10^{-11} dyn cm^{-2}) equals the pressure in the X-ray gas at the same distance from the centre of the gas distribution. A comparison of the internal and external pressures in a large sample of 39 FRII radio galaxies (Rawlings 1990) suggested static pressure equilibrium for lobes located in the denser environments of clusters, where the external pressures are determined with smaller uncertainties, and where the effects of any IGM are small.

These studies indicate that, in general, the minimum internal pressures of diffuse structures in FRII radio galaxies equal the pressure of the ambient media in cases where detectable X-ray gas surrounds the radio feature. The approximate equality in the measured internal and external pressures, in these cases where the external pressures can be estimated directly from the X-ray emission, justifies the equipartition assumption that was used in deriving internal pressures in the diffuse radio lobes. Moreover, the studies indicate that the diffuse features (with lower internal pressures) located outside these high-density environments may be in equilibrium with an ambient medium whose emissivity is not directly detectable.

Outside the coronal gas of galaxies, and outside cluster environments, the internal pressures in diffuse radio structures are found to be significantly lower. Waggett, Warner & Baldwin (1977) compared the physical properties of four giant radio galaxies with linear extents exceeding 1 Mpc and found that the lobe pressures were in the range $4–7 \times 10^{-14}$ dyn cm^{-2}. In the most careful study of this kind to date, Saripalli (1988) estimated the energy densities in the *bridges* of a sample of eight giant radio galaxies. The selected regions are expected to be the 'oldest' parts of the lobes (Scheuer 1974) and are most likely to have reached an equilibrium state. The parent galaxies were all confirmed as being field galaxies which were not associated with any clusters of galaxies. This finding was based on a quantitative study of the clustering properties of galaxies located in the vicinity of the parent galaxies on the celestial sphere. All eight sources had linear sizes exceeding 1.5 h_{50}^{-1} Mpc and had edge-brightened structures. The diffuse emission in all the sources was represented in radio images at a frequency below 1.5 GHz that resolved well the sources along their lengths. The energy densities were computed within the diffuse bridges at locations $>200\, h_{50}^{-1}$ kpc from the central engine (and therefore well outside any galactic coronal halo) and far from the hotspots and associated tails of emission at the extremities of the radio lobes. Standard minimum-energy assumptions (Miley 1980) were made and the energy density was assumed to be in equipartition between the magnetic field and particles, with equal energies in relativistic electrons and other particles. A Hubble constant of 50 km s^{-1} Mpc^{-1} was adopted. A list of the eight sources studied by Saripalli (1988), their redshifts, the linear sizes and radio powers of the entire sources and the inferred minimum pressures in the bridge components are reproduced in Table 1. The minimum pressures were found to lie in the range $1–3 \times 10^{-14}$ dyn cm^{-2}. These values are significantly lower than the results of Waggett et al. (1977), primarily because Saripalli (1988) subtracted compact features (e.g. jets, knots of emission, background sources) from the images before deriving parameters for the diffuse emission. The pressures inferred by Saripalli (1988) are therefore representative of the diffuse bridges alone, whereas the derivations of Waggett et al. refer to the entire lobe including any jets, hotspots and other compact features. The remarkably small scatter suggests that these regions, located about 200–500 h_{50}^{-1} kpc from the centres of the parent galaxies, are in static equilibrium with a uniform external medium. In Fig. 1, we reproduce a plot of the minimum pressure versus the redshift of the parent radio galaxy. The errors in the derived pressures are dominated by the uncertainties in the spectral indices of the bridge com-

Table 1. Properties of the giant radio galaxies studied by Saripalli (1988).

Source	Redshift z	Linear size (Mpc)	Radio power at 408 MHz (10^{26} W Hz^{-1})	Minimum bridge pressure (10^{-14} dyn cm^{-2})
0114-476	0.146	2.0	10.4	1.8
0211-479	0.22	1.6	8.5	3.1
0503-286	0.038	2.5	0.7	1.8
DA 240	0.0356	2.0	0.9	1.0
4C73.08	0.0581	1.7	1.5	2.0
3C236	0.0988	5.7	4.9	1.1
1452-517	0.08	2.5	1.5	1.5
3C326	0.0895	2.7	4.0	3.0

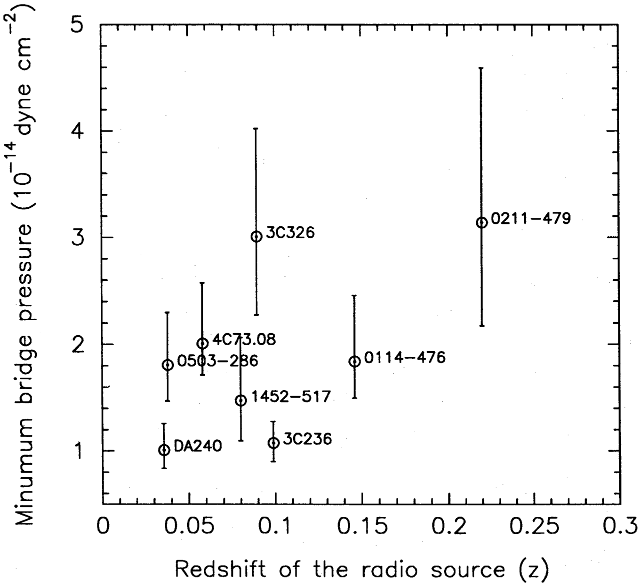

Figure 1. Minimum pressures derived for the bridges of the sample of giant radio sources in Table 1 plotted as a function of the redshift z of the parent galaxy. The error bars correspond to an assumed error of ± 0.2 in the bridge spectral index. Reproduced from Saripalli (1988).

ponents. Interestingly, there is marginal evidence for a decrease in pressure with cosmic epoch, consistent with the expected decrease in pressure of any non-relativistic IGM with cosmological expansion. The results are indicative of an IGM with a present-day pressure of $P_o \sim 10^{-14}$ dyn cm^{-2}. Accounting for the errors in the estimates of the minimum pressures in individual sources, absolute limits to P_o are 0.5 and 2×10^{-14} dyn cm^{-2}.

It has been suggested (Waggett et al. 1977) that commonality in derived pressures could be a consequence of an observational selection effect arising from similar sensitivity limits of the telescopes used. The sources were identified in surveys as candidate giant sources either because they appeared as a pair of closely located sources with indications of physical association, or because they appeared to lie in confused regions. The surveys detected only the brightest parts of the sources. Most surveys are confusion-limited to sources with brightness below about 6 mJy arcmin^{-2} at 1 GHz (Baldwin 1984). The giant sources in the sample were detected in surveys with brightness in the range 30–200 mJy arcmin^{-2}, that is spread well above this confusion limit. More importantly, the low surface brightness bridges that Saripalli (1988) used to derive the IGM pressures were detected in the subsequent sensitive imaging with intensities that were a factor 8–34 above the rms noise. These indicate that the small scatter in the derived bridge pressures is not likely to be an observational selection effect.

High angular resolution observations of the powerful radio galaxy Cygnus A have revealed filamentary structure in the lobes (Perley, Dreher & Cowan 1984). Low filling-factors in the synchrotron-emitting plasma that constitutes the radio bridges would imply an increased minimum-energy density in the emitting medium. Therefore, the assumption of unity filling-factor made in Saripalli (1988) would only lead to an underestimation of the bridge pressures. If the assumption of equipartition were violated, or the energy in electrons were significantly smaller than that in other particles, the true pressure in the synchrotron bridges would be greater than the estimate used here, and therefore the value used ($P_o \sim 10^{-14}$ dyn cm^{-2}) is strictly a lower limit to the IGM pressure. In the following section, the absence of detectable distortions in the CMB spectrum is used to derive upper limits to the IGM pressure for comparison with the P_o derived above. Consequently, the main conclusions will be independent of the assumptions of unity filling-factor and equipartition.

3 CONSTRAINTS ON THE IGM FROM *COBE*

3.1 Uniform IGM

A non-relativistic, uniform IGM in thermal equilibrium that has a present-day electron density n_o cm^{-3} and temperature T_o K will have an electron pressure whose evolution with redshift z is given by

$$P(z) = kn_o T_o (1+z)^5 = P_o (1+z)^5 \text{ dyn cm}^{-2}, \quad (1)$$

where k is the Boltzmann constant and P_o the present-day pressure. A standard Friedmann cosmology, with present-day Hubble constant H_o, density parameter Ω_o and a zero cosmological constant is adopted. During epochs $z \lesssim 6$, expansion cooling will dominate cooling due to thermal bremsstrahlung emission and inverse Compton scattering of the CMB photons, on the very reasonable assumptions that the baryon density parameter $\Omega_b \lesssim 1$, and that the uniform IGM has a temperature 10^{-4} eV$\lesssim kT \lesssim 500$ keV. We assume, therefore, that the IGM was ionized and heated to the temperature of $T_o(1+z_h)^2$ K at the redshift $z_h \lesssim 6$ and thenceforth cooled adiabatically due to the Hubble expansion. The traversal of the CMB photons through this IGM will result in a spectral distortion characterized by the y-parameter:

$$y = \frac{\sigma_T P_o}{m_e c H_o} \int_0^{z_h} \frac{(1+z)^3 \, dz}{(1+\Omega_o z)^{1/2}}, \quad (2)$$

where m_e is the electron rest mass, σ_T is the Thomson cross-section and c is the speed of light in vacuum.

The far-infrared absolute spectrophotometer (FIRAS) on the Cosmic Background Explorer has not detected deviations in the CMB spectrum from Planck form, and preliminary limits are $|y| \lesssim 10^{-3}$ (Mather et al. 1990). In equation (2), we adopt the values of $P_o = 10^{-14}$ dyn cm^{-2} inferred for the uniform IGM from estimates of the internal pressures of bridges of giant radio galaxies. We then plot in Fig. 2 the expected distortion in the CMB spectrum (y) versus the redshift of reheating for the IGM (z_h). The current *COBE* upper limits on y rule out $z_h > 1.5$. We conclude that, if the low-redshift radio bridges are in equilibrium with their environment, the IGM must have been reheated at $z \lesssim 1.5$.

Within the framework of the hot big-bang cosmology, the primordial ^{7}Li abundance has been used to set an upper limit of $\Omega_b < 0.1\ h_{50}^{-1}$ on the baryon density of the Universe (Kawano, Schramm & Steigman 1988). Consequently, $\Omega_{IGM} < 0.1$, and this upper limit on the density of the IGM, together with the estimate of $P_o = 10^{-14}$ dyn cm^{-2}, implies a lower limit of $T_o > 1.6 \times 10^7$ K on the present-day temperature of the IGM. The observable Universe out to redshifts $z \sim 1.5$ does not show any evidence for violent phenomena that could transfer an energy density of about $u = (3/2)P_0(1+z)^5 = 0.01(1+z)^5$ eV cm^{-3} into the IGM and heat the constituent particles to energies $kT > 1.4$ keV. Galaxies and QSOs are observed up to $z \sim 3$–4, implying that the epoch of galaxy formation was at $z \gtrsim 4$–5. Therefore, a hot IGM existing today would be expected to have been formed at $z_h \gtrsim 4$–5. Consequently, *COBE* limits on y appear to rule out an IGM with $P_0 = 10^{-14}$ dyn cm^{-2} and we consider it unlikely that the diffuse and relaxed bridges of extended radio galaxies are in static equilibrium with a uniform environment.

3.2 Inhomogeneous IGM

The mean distortion expected in the CMB spectrum would be reduced if the IGM were clumped. An important constraint on possible IGM clumping is the isotropy of the brightness temperature of the CMB. It may be noted here that a 'two-component' IGM consisting of non-relativistic components in pressure equilibrium would not be expected to produce CMB anisotropies, but would produce the same CMB distortion as a uniform IGM with the same pressure. A model in which non-relativistic IGM clumps are pressure-confined by higher temperature semirelativistic gas (see, e.g., Barcons & Fabian 1988) would result in greater CMB distortions, because the fractional energy change in the scattered photons increases with increasing electron energy (and this effect dominates the decrease in the scattering cross-section for semirelativistic electrons). In addition, the reduced cooling time-scale for semirelativistic gas (for cooling due to inverse Compton scattering of the CMB) would imply a low reheating redshift of $(1+z_h) \lesssim 6(1+4kT_e/m_e c^2)^{-2/5}$ if a significant part of the heat put into the higher temperature gas component is not to be drained into the CMB. A clumpy IGM that is devoid of any significant gas outside the clumps would result in anisotropies in the CMB temperature due to variations in the 'y-parameter' along different lines of sight.

The bridge pressures of giant radio sources seem indicative of redshift evolution (Saripalli 1988) and we model the IGM clumps as having a constant co-moving size since the reheating redshift of $z_h \sim 4$–5. The clumping may be quantified in terms of a filling factor f, which is the equivalent fractional volume occupied by the IGM clumps. Since the IGM clumps are constrained to have pressures $P(z) = 10^{-14}(1+z)^5$ dyn cm^{-2} equal to the internal pressures in the radio bridges, the mean CMB distortion $\bar{y}$ will be a factor f below that shown in Fig. 2. For $z_h \sim 4$–5, a distortion corresponding to $y = 0.02$ is expected for a uniform IGM and therefore the distortion in a clumped IGM will be $\bar{y} = 0.02f$. The clumpy IGM will be expected to produce fractional temperature fluctuations in the CMB of magnitude $\Delta T/T = 2\bar{y}/\sqrt{N}$, where N is the mean number of IGM clumps in the telescope beam. Adopting an Einstein–de Sitter cosmology, the number of clumps expected in a beam of size θ_b arcmin is $N = 10^4\, h_{50}^{-3}\, D^{-3}\, \theta_b^2$, where D is the characteristic clumping scale in Mpc. To date, the most stringent upper limit to the product $(\Delta T/T \times \theta_b)$ has been that $\Delta T/T < 1.7 \times 10^{-5}$ on a scale of 2 arcmin (Readhead et al. 1989). This leads to the constraint

$$f(Dh_{50})^{3/2} < 0.1, \qquad (3)$$

relating the filling factor to the clumping scale. The relationship between $\bar{y}$, f and D is depicted in Fig. 3 as the continuous line, where the parameter space to the lower left of the line is allowed by the CMB isotropy constraint. The preliminary *COBE* limit of $y < 10^{-3}$ constrains the filling factor f to be < 0.05. Therefore, current limits on CMB anisotropy and spectral distortion do not rule out the possibility of a clumped IGM with a clumping scale 1–10 Mpc and with pressures $P(z) = 10^{-4}(1+z)^5$ dyn cm^{-2} within the clumps, but constrain the filling factor to small values ($f < 0.05$–0.005).

Within superclusters, the bright galaxies have a mean density $\sim(6.3\ h_{50}^{-1}$ Mpc$)^{-3}$ and the galaxy–galaxy two-point correlation function causes their nearest-neighbour distance to be about 1 h_{50}^{-1} Mpc (Peebles 1980). The bridge regions in

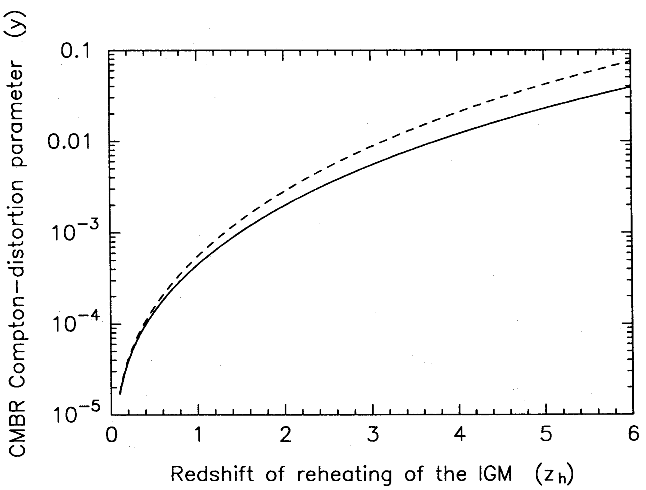

Figure 2. Expected Compton distortion y-parameter as a function of the redshift of reheating of the IGM (z_h). The curves plotted assume a Friedmann cosmology with density parameter $\Omega_0 = 0.1$ (dashed line) and 1.0 (continuous line). The present-day pressure in the IGM is assumed to be 10^{-14} dyn cm^{-2}. The cosmological constant is assumed to be zero.

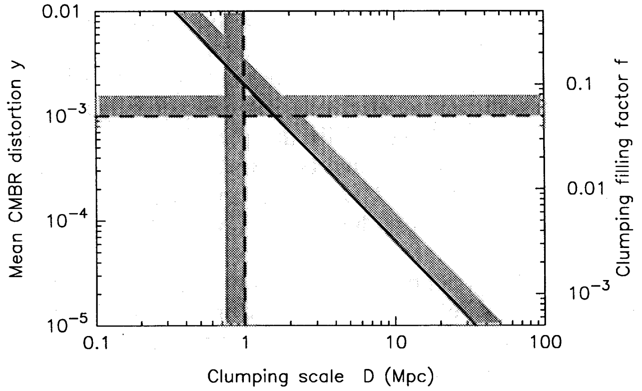

Figure 3. Constraints on the clumping scale and filling-factor of an inhomogeneous IGM. The constraint from limits to the anisotropy of the CMB is shown by the continuous line. Dashed lines indicate the current upper limit on y from *COBE* measurements and the approximate lower limit on clumping scale D from the sizes of the giant radio sources. The allowed parameter space is delineated.

the giant radio sources are located at about 0.5 h_{50}^{-1} Mpc from the centres, suggesting that the sizes of the IGM clumps and the characteristic clumping scale, D, are $\gtrsim 1$ Mpc. We now assume that any IGM surrounding the isolated giant radio galaxies is typical of the medium around all bright galaxies in the field. Consequently, IGM clumps of ~ 1 Mpc size would be expected to have characteristic distances between the IGM clumps that are not much larger than the sizes of the clumps themselves, and this suggests that $f \gtrsim 0.1$. The large-scale spatial distribution of galaxies indicates that underdense regions (voids) occupy about 80 per cent of volume (Huchra et al. 1988), suggesting that, if the IGM clumping were associated with superclusters (rather than galaxies), the filling factor $f \gtrsim 0.2$. A comparison of these lower limits to possible clumping of the IGM, with the upper limits derived above from current upper limits on CMBR distortions and anisotropies, leads us to infer that a clumpy IGM is unlikely.

If, on the other hand, IGM clumping displays a wide range of scales, with the giant radio galaxies efficiently tracing IGM clumps of the largest scale, small filling-factors are possible and such an inhomogeneous IGM cannot be ruled out by the above-mentioned considerations.

3.3. Uniform IGM without thermal equilibrium

In the preceding sections, the internal pressures in radio bridges have been used as an estimate of the total pressure of the external IGM. The pressure of the hot ionized IGM is composed of the partial pressures of its constituents – electrons and nuclei. The CMB distortion, as characterized by the y-parameter, is the sum of contributions due to inverse Compton scattering off the hot electrons and nuclei. Since y is proportional to the average change in photon energy per scattering (which depends inversely on the mass of the scattering particle) and the Thomson scattering cross-section (which depends inversely on the square of the mass of the scattering particle), the y contribution from any one of the singly charged species x would be proportional to T_x/m_x^3 where T_x and m_x are, respectively, the temperature and rest mass of particles of species x. Since the particle mass ratio $(m_e/m_p)^3$ is of order 10^{-10} (where e and p refer to electrons and nuclei respectively), the total y distortion is essentially proportional to the partial pressure of the electrons alone in most astrophysical conditions. Therefore, if the IGM were composed of hot nuclei that were not in thermal equilibrium with lower temperature electrons, and consequently the total IGM pressure were essentially the partial pressure of the nuclei, the y-parameter would be reduced below that shown in Fig. 2 by a factor T_e/T_p. Such an IGM may not be constrained by current limits on CMB anisotropy and spectral distortion.

Energy that is put into ionized gas by shocks and gravitational potentials effectively heats the more massive nuclei (rather than electrons). Coulomb interactions between the nuclei and electrons transfer the heat to the electrons and the system evolves towards thermal equilibrium. For an IGM with non-relativistic particles, the time evolution of the electron temperature is approximately given by

$$\frac{\mathrm{d}T_e}{\mathrm{d}t} = \frac{T_p - T_e}{\tau_{eq}}, \tag{4a}$$

$$\tau_{eq} = \frac{8.4 \times 10^8}{\Omega_{IGM}(1+z)^3} \left(\theta_p = \frac{m_p}{m_e} \theta_e \right)^{3/2} \mathrm{yr} \tag{4b}$$

(Spitzer 1962, Stepney & Guilbert 1983). In this expression τ_{eq} represents an 'equilibration' time-scale; $\theta_e = kT_e/(m_e c^2)$ and $\theta_p = kT_p/(m_e c^2)$ are normalized dimensionless temperatures of the electrons and nuclei respectively.

We assume that the IGM was reheated at some redshift z_h and at that time the temperatures of its constituents were $(m_e/m_p)\theta_p \lesssim \theta_e < \theta_p$. At the reheating epoch z_h, the nuclei are heated to a temperature $\theta_p = P(z_h)/(n_p m_e c^2)$, where $P(z) = 10^{-14}(1+z)^5$ dyn cm^{-2} is the pressure of the IGM at redshift z, and n_p is the number density of the nuclei. Therefore, the quantity $[\theta_p + (m_p/m_e)\theta_e]$ in equation (4b) will equal approximately $2\theta_p$ and evolve towards $(m_p/m_e)\theta_p$. These correspond to a temporal increase of the dimensionless quantity $[\theta_p + (m_p/m_e)\theta_e]$ from $0.01(1+z_h)^2/\Omega_{IGM}$ towards $10(1-z_h)^2/\Omega_{IGM}$. As heat is transferred to the electrons and the electron temperature rises towards the temperature of the nuclei, the equilibration time-scale τ_{eq} also increases and $\mathrm{d}T_e/\mathrm{d}t$ decreases. During the evolution, the equilibration time-scale τ_{eq} increases from a value of $8 \times 10^5 \Omega_{IGM}^{-5/2}$ yr towards the value $3 \times 10^{10} \Omega_{IGM}^{-5/2}$ yr. For the adopted Hubble constant $H_o = 50$ km s^{-1} Mpc^{-1} and density parameter $\Omega_o = 1.0$, the expansion time-scale (age) of the Universe at redshift z is $\tau_H = 1.3 \times 10^{10}(1+z)^{-3/2}$ yr. If the reheated IGM at redshift z_h has a density corresponding to $\Omega_{IGM} = 0.02$, the equilibration time-scale will exceed the present age of the Universe and there will be no significant heating of the electrons. Primordial nucleosynthesis (Kawano et al. 1988) suggests that $\Omega_{IGM} < 0.1$. If the heated IGM has a density as high as $\Omega_{IGM} = 0.1$, the initially low value of the equilibration time-scale will cause the electron temperature to rise significantly. However, once T_e attains a value $\lesssim 0.1\,T_p$, the equilibration time-scale will become larger than the present Hubble age of the Universe and the electron temperature will not increase significantly any further. The process of reheating may also compress the IGM gas to higher densities than the mean, but provided the local densities do not exceed 10 per cent of closure density ρ_c, temperature inequilibrium could be preserved. We conclude, therefore, that it is possible for a low-density IGM to have been heated and maintained in a state where the nuclei are at a significantly higher temperature than the electrons. Such an IGM that has a pressure sufficient to confine, statically, the diffuse radio bridges could have y-distortion parameters and CMB anisotropy that are at least an order of magnitude lower than those for an IGM in equilibrium. Current limits on y and CMB anisotropy cannot exclude this IGM model.

There exists observational evidence (Vallee 1990 and references therein) for primordial magnetic fields in the intergalactic space with an energy density $\sim 10^{-14}$ erg cm^{-3} similar to that inferred for the IGM. In the presence of such a magnetic field, the particles in an IGM with the pressures and densities considered above would have a Larmor radius $\sim 10^{10}$ cm, much greater than interparticle distances but much smaller than galactic distances. The presence of such a weak primordial magnetic field in the ionized IGM will not alter the equilibration time-scale significantly, but will strongly reduce the conductivity of localized heat put into the IGM. Magnetic fields could preserve large-scale inhomogeneities created during the heating of an IGM.

Subrahmanyan & Cowsik (1989) showed that the infall heating of primordial baryonic gas in supercluster potential wells could result in temperatures of order

$$kT_{\rm inf} \sim \frac{GMm_{\rm p}}{r} \sim 10^2 \left(\frac{M}{10^{16}\,{\rm M}_\odot}\right)\left(\frac{R}{10\,{\rm Mpc}}\right)^{-1} {\rm keV} \qquad (5)$$

and, consequently, produce the diffuse X-ray background. Surprisingly, only a small fraction of the infall energy appears as the background radiation; the bulk of the energy is not visible in radiant form. If the infall energy were channelled (possibly through shocks) into an IGM with a baryon density $\Omega_{\rm B}=0.02$ (where equilibration is ineffective), the energy could be locked in the heated nuclei. Such an IGM is expected to have an energy density $u \sim (\Omega_{\rm B}\rho_{\rm c}/m_{\rm p})kT_{\rm inf} \sim 10^{-14}$ erg cm^{-3}, and this is similar to the expectation for the IGM that was inferred from the internal pressures in the giant radio sources. An IGM with $P_{\rm o}=10^{-14}$ dyn cm^{-2} could therefore have a natural link with the process of galaxy formation.

4 DISCUSSION AND SUMMARY

Cowsik & Kobetich (1972) first proposed that the diffuse X-ray background (XRB) is free–free radiation from a uniform IGM that was reheated at some redshift $z_{\rm h}$. Since inverse Compton cooling dominates adiabatic expansion cooling for the IGM at redshifts $z>6$, and the observed XRB spectrum is incompatible with the spectral shape of thermal emission from an inverse Compton cooled plasma, $z_{\rm h}<6$ (Guilbert & Fabian 1986). Adopting $z_{\rm h}\sim 4$, the uniform IGM is required to have a density $\Omega_{\rm B}=0.21$ and present-day temperature $kT_{\rm o}\sim 25$ keV in order to produce the observed XRB intensity (Barcons 1987). These parameters correspond to a present-day IGM pressure $P_{\rm o}>2\times10^{-14}$ dyn cm^{-2}. Lower values of $z_{\rm h}$ constrain the IGM density and present-day temperature (and consequently $P_{\rm o}$ as well) to higher values. The upper limits on $\Omega_{\rm B}$ from primordial nucleosynthesis (Kawano et al. 1988) and, more importantly, the implications of *COBE* limits on the distortion of the CMB spectrum (Fig. 2) disallow a uniform IGM with the parameters required to produce the XRB. Recent work (Barcons & Fabian 1988; Subrahmanyan & Cowsik 1989; Barcons, Fabian & Rees 1991) has suggested thermal emission from hot gas clumps as the origin of the XRB, and the arcmin-scale isotropy of the CMB temperature led to the constraint that the clumps were of galactic scale or smaller. However, Rogers & Field (1991) derived further constraints on gravitationally confined thermal clumps from the number of observed gravitationally lensed quasars and constraints from free-expansion time-scales for clumps that are not gravitationally bound. They inferred that the XRB does not originate in thermal bremsstrahlung from gas heated only once. The XRB probably originates in discrete sources where a continuous source of energy exists and, to summarize, the XRB is *not* direct observational evidence for an IGM. The emphasis, therefore, has to be on employing astronomical objects as probes of the proposed IGM.

The similarity in minimum pressures in the bridges of giant radio sources indicates the existence of a uniform IGM with present-day pressure $P_{\rm o}=10^{-14}$ dyn cm^{-2}. We have examined the constraints on such an IGM from the *COBE* FIRAS experiment. Any IGM is expected to have been reheated at $z_{\rm h}\gtrsim 4$–5 and *COBE* limits on distortions to the CMB spectrum rule out a uniform IGM with the indicated pressure. A clumpy IGM model is not ruled out by the constraints placed by the isotropy of the CMB, but the *COBE* distortion limits require the clumping to have a small filling-factor, and this is unlikely, given the extents of the radio structures. These arguments suggest that the radio structures are probably not in any pressure balance with an IGM, and the radio bridges are perhaps expanding freely. The similarity in axial ratios between the giant sources and smaller sized sources of the same class (Leahy & Williams 1984) supports such a conclusion. If the IGM is not a significant determinant of the internal properties of the tenuous radio structures, the origin of the commonality in bridge pressures would have to be intrinsic to the radio source phenomenon.

If we constrain $z_{\rm h}\sim 4$–5 (larger values of $z_{\rm h}$ are unlikely because Compton cooling of the IGM against the CMB is expected to be very effective at higher redshifts), current *COBE* limits on $y(|y|<10^{-3})$ require the present-day pressure of any uniform IGM to be an order of magnitude lower than the minimum internal pressures inferred for the diffuse bridges of the giant radio galaxies. It has been pointed out (Rawlings 1990) that the bow-shock of a developing radio source could heat the local environment of the radio galaxy and thereby typically raise the pressure of the ambient medium by a factor of 10. Such a phenomenon could reconcile the order-of-magnitude overpressures in the bridges with respect to a uniform IGM.

However, a low-density IGM consisting of hot nuclei and cold electrons, with an equilibration time-scale exceeding the Hubble time, need not be discordant with the CMB isotropy and spectral measurements, and could confine statically the diffuse radio features of the giant radio sources. The total energy density in such an IGM could equal the total gravitational potential energy released during the non-linear evolution of the IGM baryons in a neutrino-dominated Universe. Therefore, the *value* of the IGM pressure may be a natural consequence of the formation of large-scale structures in the Universe.

ACKNOWLEDGMENTS

We thank Dr R. D. Ekers and Professor W. Kundt for their critical reading of the manuscript. The comments of the anonymous referee have been very useful in improving and clarifying the arguments.

REFERENCES

Arnaud K. A., Fabian A. C., Eales S. A., Jones C., Forman W., 1984, MNRAS, 211, 981
Baldwin J. E., 1984, in Roberts J. A., ed., Indirect Imaging. Cambridge Univ. Press, Cambridge, p. 11
Barcons X., 1987, ApJ, 313, 547
Barcons X., Fabian A. C., 1988, MNRAS, 230, 189
Barcons X., Fabian A. C., Rees M. J., 1991, Nat, 350, 685
Begelman M. C., Blandford R. D., Rees M. J., 1984, Rev. Mod. Phys., 56, 255
Cowsik R., Kobetich E. J., 1972, ApJ, 177, 585
Fanaroff B. L., Riley J. M., 1974, MNRAS, 167, 31P
Forman W., Jones C., Tucker W., 1985, ApJ, 293, 102

Guilbert P. W., Fabian A. C., 1986, MNRAS, 220, 439
Gunn J. E., Peterson B. A., 1965, ApJ, 142, 1633
Huchra J., Geller M., de Lapparent V., Burg R., 1988, in Audouze J., Pelletan M.-C., Szalay A., eds, Proc. IAU Symp. 130, Large Scale Structures of the Universe. Reidel, Dordrecht, p. 105
Kawano L., Schramm D., Steigman G., 1988, ApJ, 327, 750
Leahy J. P., Williams A. G., 1984, MNRAS, 210, 929
Mather J. C. et al., 1990, ApJ, 354, L37
Miley G. K., 1980, ARA&A, 18, 165
Miller L., Longair M. S., Fabbiano G., Trinchieri G., Elvis M., 1985, MNRAS, 215, 799
Peebles P. J. E., 1980, in Balian R., Audouze J., Schramm D. N., eds, Cosmologie Physique. North-Holland, Amsterdam, p. 213
Perley R. A., Dreher J. W., Cowan J. J., 1984, ApJ, 285, L35
Rawlings S., 1990, in Hollenbach D. J., Thronson H. A., Jr, eds, Proc. 2nd Wyoming Conf., The Interstellar Medium in External Galaxies. NASA Scientific and Technical Information Division, Washington, D.C., p. 188
Readhead A. C. S., Lawrence C. R., Myers S. T., Sargent W. L. W., Hardebeck H. E., Moffet A. T., 1989, ApJ, 346, 566
Rogers R. D., Field G. B., 1991, ApJ, 366, 22
Sarazin C. L., 1986, Rev. Mod. Phys., 58, 1
Saripalli L., 1988, PhD thesis, Indian Institute of Science, Bangalore
Scheuer P. A. G., 1974, MNRAS, 166, 513
Spitzer L., 1962, Physics of Fully Ionized Gases. Wiley, New York
Steidel C. C., Sargent W. L. W., 1987, ApJ, 318, L11
Stepney S., Guilbert P. W., 1983, MNRAS, 204, 1269
Subrahmanyan R., Cowsik R., 1989, ApJ, 347, 1
Vallee J. P., 1990, AJ, 99, 459
Waggett P. C., Warner P. J., Baldwin J. E., 1977, MNRAS, 181, 465
Zeldovich Ya. B., Sunyaev R. A., 1969, Astrophys. Space Sci., 4, 301