THE INTERGALACTIC MEDIUM

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ABSTRACT

The density of intergalactic gas may be an important parameter in the formation of extended radio sources. It may range from ~ 0.1 particle cm^{-3} in the centres of some rich clusters of galaxies down to $10^{-8} cm^{-3}$ or less in intercluster space. The possible influence of the intracluster gas surrounding NGC 1275 on its radio emission is discussed, and the possibility that a significant fraction of the X-ray background is due to a hot intergalactic medium is explored in some detail.

1. INTRODUCTION

The density of intergalactic matter has only been measured in the cores of clusters of galaxies. This gas emits X-radiation primarily by thermal bremsstrahlung and its density often exceeds 10^{-3} particles cm^{-3} in rich clusters. Little is known about the gas density at the edges of clusters (i.e. several Mpc from the centre), near relatively isolated galaxies or in intercluster space. All galaxies produce gas from stellar mass loss, and many are assumed to lose gas in the form of a wind. This, together with an expectation that galaxy formation is not 100 percent efficient, suggests that an intergalactic medium pervades most of space, with a density that probably depends fairly strongly on the local galaxy environment.

Circum- and possibly inter-galactic gas is an important ingredient in most theories of extended radio sources, both as a means of confining the radio-emitting plasma and in providing a 'working surface' for stimulating particle acceleration and emission (see e.g. De Young 1977). Unfortunately, these theories are not yet developed to the point where unambiguous particle densities may be inferred from properties of the radio emission, nor are the observed properties clearly related to the local environment (see Stocke 1979 and references therein). We shall concentrate here on those regions where we can estimate the particle densities with some accuracy, i.e. the clusters of galaxies, and on

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the possibility that a diffuse hot intercluster medium is detected as the X-ray background. The likely evolution of these examples of intergalactic gas may relate to the evolution of radio sources.

2. LOCALISED INTERGALACTIC GAS

a) The Intracluster medium

The X-ray emission from intracluster gas has been reviewed here by Jones (1982). The iron line emission features in the X-ray spectra of rich clusters suggests that much of this gas has been expelled or stripped from the member galaxies. This gas has a well observed effect on the radio sources associated with moving galaxies, producing head-tail sources such as discussed here by Harris (1982).

The gas density in some of the rich clusters such as A1656 in Coma does not exceed $\sim 5 \times 10^{-3}\mathrm{cm}^{-3}$ and so radiative cooling is not of importance on a Hubble time. In a number of other clusters, however, the density is much greater. Cooling flows (Fabian & Nulsen 1977, Cowie & Binney 1977) occur in the cores of these clusters, with densities surrounding the central galaxy approaching $\sim 0.1\ \mathrm{cm}^{-3}$. The region around NGC 1275 (3C84, Per A) in the Perseus cluster is a good example, in which $\sim 300\ M_\odot\ \mathrm{yr}^{-1}$ is being accreted by the pressure of the outer hot material (Fabian *et al.* 1981). The pressure of the surrounding gas is ~ 100 times the pressure in the local interstellar medium in our Galaxy. It seems possible that this could frustrate a nascent extended radio source. The inertia of the high-density cooling flow would be a severe impediment to a supersonic outflow. Nevertheless, extended radio emission is observed around NGC 1275 on most scales out to ~ 3 arcmin (Ryle & Windram 1968, Miley & Perola 1975, Gisler & Miley 1979, Reich *et al.* 1980, Noordam & de Bruyn 1982). The large-scale radio blob, lying $\sim 2\frac{1}{2}$ arcmin SW of the nucleus, may have been produced by some jet from NGC 1275, or it may be some relic of the slow motion of the galaxy in the cluster core. Studies of this source should provide information on extended radio emission in high-pressure environment. Stewart *et al.* (1981) find traces of weak X-ray emission leading from the nucleus to this blob. An inverse-Compton interpretation, similar to that used for the extended M87 structures found by Schreier (1982), suggests a weak magnetic field ($B \sim 10^{-7}$G; $B^2/8\pi \ll$ thermal pressure) in that region. The cosmic ray electrons may be in pressure equilibrium. Much more precise measurements of the radio (and preferably X-ray) spectral index are necessary before any firm conclusion may be reached.

It seems possible that much of the amorphous radio structure observed on a scale of ~ 30 arcsec could be directly associated with the accretion flow. The thermal instability causes rapid changes of density (and shocks) to occur in the cooling intracluster gas, much of which was presumably interstellar gas at some stage. It may thus contain magnetic fields and cosmic ray electrons from this earlier phase, which

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will then be amplified in the flow. It is not therefore surprising that an unstructured radio source is found in the centre of such a flow, although the energetics are admittedly uncertain. Similar amorphous sources should occur in most such cooling flows.

b) The Edges of Clusters

The X-ray emission from clusters is only well studied by current imaging techniques out to 1 or 2 Mpc from the centre. Beyond the core we can expect that conditions are mostly determined from the early phases of the formation of the cluster and that cooling is totally unimportant. The accretion of sub-clusters and the dynamical evolution of the cluster galaxies may, however, lead to some resettlement of the gas. It is possible that radio sources heat the gas significantly (cf. Lea & Holman 1978), but if this is a common occurrence we might wonder why any gas at all has remained. For the present we can only make crude estimates of the density falloff at large distances from the cluster centre. At radii approaching and exceeding 10 Mpc, the assumption of hydrostatic pressure balance probably breaks down as this is the distance that sound waves (in a gas at $\sim 10^8$K) can even out any imbalance. A slow net inflow, or outflow, of intracluster gas may be established at intermediate radii.

c) Isolated Galaxies

Little is known of the intergalactic environment surrounding relatively isolated galaxies. As already mentioned, galactic winds may transport some of the interstellar medium of such galaxies up to several Mpc in a vacuum. However, even a very-low density uniform intercluster gas confines such a wind to within a few 100 kpc. Perhaps the best evidence for matter at large ($\sim$ 100 kpc) distance around isolated galaxies is to be found in the shells discovered by Malin & Carter (1980). (For an interpretation in terms of galactic winds see Fabian *et al.* 1980).

3. A DIFFUSE INTERCLUSTER GAS

Observations of enormous radio sources such as DA 240, NGC 6251 and 3C236 (e.g. Strom *et al.* 1980) provide some support for a tenuous intercluster medium. The most tantalising evidence is the X-ray background. The spectral shape of the $\sim$ 3 - 40 keV background was noted to be consistent with thermal bremsstrahlung from a diffuse hot (kT $\sim$ 40 keV) gas by Cowsik & Kobetich and by Field in 1972. This provides either a measurement or a limit on a hot intercluster gas. Constraints on any lower temperature ($T < 10^7$K) medium rely on ultraviolet (see Parasce *et al.* 1980) or optical (see Young *et al.* 1980) measurements and are not discussed here. (Nor are implications for the survival of cold clouds, see Cowie & McKee 1975). It is possible that the X-ray background provides us with a direct measurement of the intercluster medium.

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The 3 - 400 keV spectrum of the X-ray background (Fig. 1) has been accurately measured by the HEAO-1 satellite (3 - 50 keV, Marshall *et al.* 1980; ∿ 100 - 400 keV, Matteson *et al.* 1979) and by balloon (∿ 25 - 150 keV, Kinzer *et al.* 1978). (A composite spectrum from 1 keV to ∿ 100 MeV due to R. Kinzer is shown in Fabian 1981). A bump observed in the spectrum at ∿ 1 MeV is plausibly attributed to unevolved active galaxies. The composite spectrum deduced from a luminosity function compiled from observed Seyfert galaxies (Piccinotti *et al.* 1981, and mean photon index of 1.7) contributes ∿ 20 percent at 3 keV and extrapolates to give all of the observed background at ∿ 1 MeV (see Boldt 1981 and references therein). We show the resultant 3 - 300 keV background spectrum after subtraction of the unevolved Seyfert component in Fig. 1.

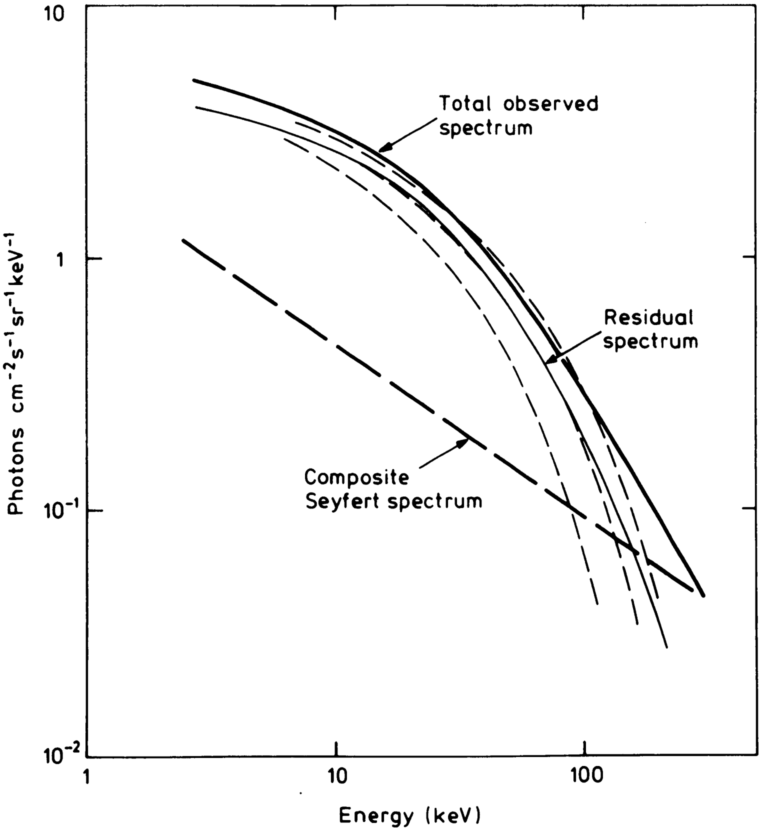

Figure 1. The total X-ray background spectrum is shown as the heavy solid line. The residual spectrum after subtraction of the composite Seyfert spectrum (heavy dashed line) is represented by the fine continuous line. Predicted spectra from intercluster gas adiabatically cooling from a redshift, z_m, of 5 to current temperatures of 6, 8 and 10 keV are shown as fine dashed lines.

The contribution of quasars to the X-ray background remains uncertain (see Tananbaum 1981). We find that at least 15 percent of the extrapolated background at 2 keV must be due to quasars (Kembhavi & Fabian 1981). It remains possible that most of the remainder could result from very faint quasars, although it should be immediately noted that most of the X-ray measurements of quasars are made at $\sim$ 2 keV, at which energy there may be an excess (Garmire & Nousik 1981) over the extrapolated background (i.e. from higher energies), and that little is known of the X-ray spectrum of most quasars. Their contribution to the 3 - 300 keV background will be ignored in the rest of this discussion. A large ($\gtrsim$ 20 percent) quasar contribution at much above 3 keV clearly changes the conclusions. The Seyfert-subtracted X-ray background spectrum (Fig. 1) is not compatible with that from a single-temperature bremsstrahlung but is consistent with a range of models involving a hot gas expanding and cooling with the Universe. Such models were first considered by Field & Perrenod (1977), who compared the total observed spectrum with that from electron-ion bremsstrahlung from a gas cooling from $z_m \simeq 3$. The particle density, n, falls as $(1+z)^3$, and thus the temperature, T, as $(1+z)^2$.

We have considered here a range of maximum redshift, z_m, and owing to the mildly relativistic nature of the electrons, electron-electron bremsstrahlung and further e-i corrections due to Gould (1980) are included. (These formulae may overestimate the e-e contribution for kT > 100 keV.) Spectra were computed for a range of initial temperatures, and the appropriate one selected by visual comparison with the residual (total-Seyfert) spectrum. This was considered reasonable considering the observational errors and possible normalization problems with three data sets. A typical fit is shown in Fig. 1. We find that the present (z=0) density, n_o, temperature, T_o, and pressure, P_o, scale as

$$n_o \simeq 2.10^{-6}\ (1+z_m)^{-1.5}\ (1+z)^3\ \mathrm{cm}^{-3}$$

$$T_o \simeq 6.10^8\ (1+z_m)^{-1}\ (1+z)^2\ \mathrm{K}$$

and $$P_o \simeq 3.2.10^{-13}\ (1+z_m)^{-2.5}\ (1+z)^5\ \mathrm{dyne\ cm}^{-2}.$$

H_o was taken as 50 km $s^{-1}Mpc^{-1}$, and $q_o = \frac{1}{2}$. Generally $H_o{}^3\ \Omega_{gas}^2$ = constant. We see that if $z_m \simeq 5$, the present intercluster density would be $\sim 10^{-7} cm^{-3}$($\Omega_{gas} \sim 0.04$) and $kT_o \sim 8$ keV.

The major problems with this explanation for the X-ray background are its energetic extravagance and inefficiency. (This may be a philosophical problem, for it also applies to many large radio sources.) Radiative cooling could never have tapped more than a few percent of the thermal energy of the gas. The total energy requirement amounts to $\sim 10^{63}\ (1+z_m)^{-\frac{1}{2}}\ N_{-2}^{-\frac{1}{2}}$ erg/galaxy, where the number density of relevant galaxies = $10^{-2}\ N_{-2}$ galaxies Mpc^{-3}. (N_{-2} = 1 corresponds to luminous spirals). This may be compared with the energy required to make the observed metals (see Bookbinder *et al.* 1980), the energy content of some radio galaxies and of massive spinning black holes, and with the output of quasars. How the gas might have been heated is a mystery (for suggestions see Field & Perrenod 1977, Sherman 1979, Bookbinder *et al.* 1980).

We note that the electron-ion coupling time generally exceeds the age of the hot gas and that then the assumption of an underlying Maxwellian distribution may fail. On the other hand, Compton cooling by the microwave background becomes a serious problem if $z_m >> 5$. The microwave background spectrum might also become noticeably distorted (see Wright 1979). Clumping of the gas to increase the radiative efficiency and ease the energy problem cannot work if z_m is small (McKee 1980, Fabian 1981) because of the strong observed isotropy limits on any origin of the X-ray background. It may yet be possible to have small-scale clumping (on an observed scale $< 5°$) if $z_m \gtrsim 3$ or so. (This requires $\gtrsim$ 100 clumps per square degree.)

4. THE INFLUENCE OF THE INTERGALACTIC MEDIUM ON RADIO SOURCES

This section is hampered by a lack of any clear understanding of the evolution of radio sources. Intracluster gas has observable consequences on radio sources in clusters. Galaxy motions (and possibly buoyancy and cluster winds) can shape extended radio emission which is also confined by thermal and ram pressure. Amorphous sources may form from cooling gas in the cores of some clusters. Henry *et al.* (1979) find little evidence for evolution in the X-ray properties of intracluster gas out to $z \sim 1$. This may be relevant to the evolution of many radio sources. A diffuse intercluster medium should evolve with $P \propto (1+z)^5$. If any radio sources are in equipartition and thermal pressure balance with such a gas, we may expect that $L \propto (1+z)^{15/4}U$, where U is the total energy. Size should scale as $R \propto (1+z)^{-3}$. Ram pressure balance gives $R \propto (1+z)^{-3/5}$. The high pressure in the past could also affect the spectral index of radio sources. However since most radio sources seem to be associated with galaxies, it could be that few such sources ever sample the true intercluster medium.

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REFERENCES

Boldt, E.A.: 1981, Comments on Astrophys. 9,pp.97.
Bookbinder, J., Cowie, L.L., Krolik, J.H., Ostriker, J.P., and Rees, M.J.: 1980, Astrophys.J. 237,pp.647.
Cowie, L.L., and Binney, J.: 1977, Astrophys.J. 215, pp. 723.
Cowie, L.L., and McKee, C.F.: 1975, Astrophys.J. 195, pp.715.
Cowsik, R., and Kobetich, E.J.: 1972, Astrophys.J. 177, pp.585.

De Young, D.S.: 1977, Ann.N.Y.Acad.Sci. 302,pp.669.
Fabian, A.C.: 1981, Ann.N.Y.Acad.Sci. (in press).
Fabian, A.C., and Nulsen, P.E.J.: 1977, Monthly Notices Roy.Astron.Soc. 18,pp.479.
Fabian, A.C., Cowie, L.L., Hu, E., and Grindlay, J.: 1981, Astrophys. J. 248,pp.47.
Fabian, A.C., Nulsen, P.E.J., and Stewart, G.C.: 1980, Nature, 287,pp.613.
Field, G.B.: 1972, Ann.Rev.Astron.Astrophys. 10,pp.227.
Field, G.B., and Perrenod, S.C.: 1977, Astrophys.J. 215,pp.717.
Garmire, G., and Nousek, J.: 1981, Bull.Am.Astron.Soc. 12,pp.853.
Gisler, G.R., and Miley, G.K.: 1979, Astron.Astrophys. 76,pp.109.
Gould, R.J.: 1980, Astrophys.J. 238,pp.1026.
Harris, D.: 1982, These proceedings, p. 77.
Henry, J.P. *et al.*: 1979, Astrophys.J. (Lett.) 234, L15.
Jones, C.: 1982, These proceedings.
Kembhavi, A.K., and Fabian, A.C.: 1981, Monthly Notices Roy.Astron.Soc. in press.
Kinzer, R.L., Johnson, W.N., and Kurfess, J.D.: 1978, Astrophys.J. 222, pp.370.
Lea, S.M., and Holman, M.D._ 1978, Astrophys.J. 222,pp.29.
Marshall, F.E., Boldt, E.A., Holt, S.S., Miller, R.B., Mushotsky, R.F., Rose, L.A., Rothschild, R.E.,and Serlemitsos, P.J.: 1980, Astrophys. J. 234,pp.4.
Malin, D.F., and Carter, D.: 1980, Nature 285,pp.643.
Matteson, J.L., Gruber, D.E., Nolan, P., Peterson, L.E., Kinzer, R.L.: 1979, Bull.Am.Astron.Soc. 11,pp.653.
McKee, C.: 1980, Physica Scripta 21,pp.738.
Miley, G.K., and Perola, G.C.: 1975, Astron.Astrophys. 45,pp.223.
Noordam, W., and deBruyn, G.: 1982, These proceedings.
Paresce, F., McKee, C.F., and Bowyer, S.: 1980, Astrophys.J. 240,pp.387.
Piccinotti, G., Mushotzky, R.F., Boldt, E.A., Holt, S.S., Marshall, F.E., and Serlemitsos, P.J.: 1981 preprint.
Reich, W., Stute, U., and Wielebinski, R.: 1980, Astron.Astrophys. 89,pp.204.
Ryle, M., and Windram, M.D.: 1968, Monthly Notices Roy.Astron.Soc. 138,pp.1.
Schreier, E.: 1982, These proceedings.
Sherman, R.D.: 1979, Astrophys.J. 232,pp.1.
Stewart, G.C., Fabian, A.C., Nulsen, P.E.J., and Phinney, S.: 1981, in preparation.
Stocke, J.: 1979, Astrophys.J. 230,pp.40.
Strom, R.G., and Willis, A.G.: 1980, Astron.Astrophys. 85,pp.36.
Tananbaum, H.: 1982, These proceedings.
Wright, E.L.: 1979, Astrophys.J. 232,pp.348.
Young, P.J. *et al.*: 1980, Astrophys.J.(Suppl.) 42,pp.41.

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