INTERGALACTIC MATTER AND RADIATION AND ITS BEARING ON GALAXY FORMATION AND EVOLUTION

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Abstract. An up-dated review is given of the evidence for the presence of intergalactic matter and radiation in the Universe. It is concluded that the only important constituents which may make a sizable contribution to the total mass-energy are intergalactic gas and condensed objects with a very high mass-to-light ratio. If the QSOs are not at cosmological distances, cold atomic hydrogen may still be the most important constituent and may contribute much more mass than do the galaxies. The X-ray observations still do not unambiguously show that very hot gas is present, though it is very likely on general grounds that some hot gas is present in clusters of galaxies.

The question of whether or not large amounts of matter, enough to close the Universe, are present, remains unsettled. From the theoretical standpoint the answer depends almost completely on the approach taken to the problem of galaxy formation and to the cosmological model which is favoured.

1. Introduction

In this paper I shall first review the evidence concerning the different forms of mass-energy in the Universe, and then turn briefly to a discussion of the bearing of these results on our understanding of the formation and evolution of galaxies.

In an earlier paper prepared for *IAU Symp.* **44** (Burbidge, 1972) I gave an extensive discussion of the evidence for intergalactic matter and radiation as it appeared in 1970. More recently Field (1972) has also reviewed the evidence for the presence of intergalactic matter. The first part of this paper is therefore concerned with the up-dating of these earlier discussions.

It is convenient to discuss the evidence under several headings:

(1) Neutrinos,
(2) Relativistic particles,
(3) Gravitational radiation,
(4) Fields of electromagnetic radiation,
(5) Diffuse gas,
(6) Mass condensations.

Following the work of Sandage (1972) and of Abell and Eastmond (1968), we put $H_0 = 50$ km s^{-1} Mpc. This means that the critical density ($q_0 = \frac{1}{2}$) necessary to 'close' the Universe, or the steady-state value, is now $\varrho_c = 4.7 \times 10^{-30}$ g cm^{-3} = 3×10^{-6} particles cm^{-3}. On the other hand, the mass density which is present in the visible galaxies, ϱ_g, lies in the range 7–13 $\times 10^{-32}$ g cm^{-3}, corresponding to a particle density of 4–8 $\times 10^{-8}$ cm^{-3} (Noonan, 1972). The discrepancy between this value and the density required to close the Universe (a factor of 30–60) is what has given rise to much speculation concerning the presence of 'missing mass'. We shall discuss the various forms of mass-energy and ask how much they might contribute to the

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total energy balance of the Universe. At the same time, it should be remembered that if we do not live in a steady-state universe of the type described by Hoyle, or if we live in an open Friedmann universe with $0<q_0 \ll 1/2$, there may not be such a large difference between the mass in galaxies and that in the Universe.

2. Neutrinos

As was pointed out in the earlier review (Burbidge, 1972) the experimental limits placed on the energy density of low-energy neutrinos from the cut-off in the β-decay spectrum are not severe. They are such that the neutrino energy density could still be many orders of magnitude above the critical density and not have been detected.

3. Relativistic Particles

We really have little idea as to what the energy density of relativistic particles amounts to. If cosmic rays are largely confined to galaxies, the mean energy density in the Universe is only about 10^{-16} erg cm$^{-3} \simeq 10^{-37}$ g cm^{-3}. If, on the other hand, the cosmic rays are universal with an energy density of 10^{-12} erg cm^{-3}, then the equivalent mass density $\simeq 10^{-33}$ erg cm^{-3}.

If the bulk of the cosmic rays has an extragalactic origin, it is likely that they are confined to clusters and superclusters, so that the universal energy density will be about 10^{-14} erg cm$^{-3} = 10^{-35}$ g cm^{-3} (Brecher and Burbidge, 1972a). Even the higher estimates only correspond to very small mass densities which do not have any appreciable effect on the evolution of the Universe.

The only point of some importance is that, if diffuse matter is present at a density $\gtrsim 10^{-30}$ g cm^{-3} in an evolving Universe, its interaction with a cosmic-ray flux with an energy density $\geqslant 10^{-12}$ erg cm^{-3} would give rise to a γ-ray flux greater than that detected. Thus we cannot have universal cosmic rays and a gas-filled Universe.

4. Gravitational Radiation

Over the last several years Weber's results suggesting that large amounts of mass $\geqslant 10^3$ $M_\odot$ yr^{-1} are being radiated in the form of gravitational waves from the galactic centre, have led to speculations that during their evolution galaxies might radiate a large amount of mass. However, it is proving difficult to confirm Weber's results, so that there is a serious question as to whether or not gravitational radiation has been detected.

Rees (1971) has argued that early in an evolving Universe there may have been a large amount of energy converted into long-wavelength gravitational waves, and that this may be present at critical density.

5. Fields of Electromagnetic Radiation

There are four distinguishable components of electromagnetic radiation in the Universe.

They are:

(a) starlight,

(b) nonthermal radio emission,

(c) diffuse X-ray and γ-ray background,

(d) microwave background radiation.

The best estimate of the energy density of starlight is still that given by Felten (cf. Burbidge, 1972) of about 1.5×10^{-14} erg cm^{-3} (1.5×10^{-35} g cm^{-3}). The energy densities of non-thermal radio emission and of the X-ray background are exceedingly small, but the X-ray background may provide evidence for the existence of hot gas. We shall discuss this later.

As far as the microwave background is concerned, there have been some recent developments. While since 1965 most people have thought it likely that the microwave background radiation was generated in a hot big-bang, the evidence that this is the case has not been unambiguous. This is due to the fact that while the measurements in the centimeter range fall very well on the Rayleigh-Jeans part of a black-body curve with a temperature of about 2.8 K, there has been considerable confusion as far as the measurements close to the peak of such a black-body curve near 1 mm are concerned. The indirect measurements using CN, CH and CH^+ all were compatible, or indicated a maximum near 1 mm, but the balloon and rocket measurements were in conflict with these, and in some cases with each other, indicating the existence of a much higher flux of radiation than that from a black-body radiation field (for references see Burbidge, 1971). It was these high measurements that led to the distinct possibility the radiation might not have arisen in a big-bang,* but that very large numbers of weak discrete sources were involved.

However, in the last six months, rocket results from Los Alamos (Williamson *et al.*, 1973) and from Cornell (Houck *et al.*, 1972) and balloon results from M.I.T. (Muehlner and Weiss, 1973), the last two groups being those which had earlier reported high fluxes, do not indicate the presence of any flux higher than that expected from a black-body radiation field at a temperature of about 2.8 K. If some of the earlier high measurements were correct at all, this flux must be variable and hence very local and not cosmological in origin.

6. Diffuse Gas

The most interest continues to centre on the possible existence of low density gas both in the outer parts of galaxies, in clusters of galaxies, and possibly even between clusters of galaxies. I last reviewed this situation some three years ago, and at that time stressed that there was no really compelling evidence for the existence of any appreciable amounts of gas anywhere outside galaxies. Field (1972) in his recent review has covered much of the same ground taking into account the most recent

* It should be stressed that the only really strong evidence for an evolving universe is the existence of a background flux which appears to have a black-body energy distribution.

X-ray data (up to 1971) and has given a slightly more optimistic discussion of the problem. I shall now up-date the discussion further.

6.1. Detection of Neutral Atomic Hydrogen

The methods that have been used are to attempt to detect 21-cm absorption or emission in the spectra of radio galaxies or QSOs, or to detect Lα absorption in the spectra of QSOs. As far as the 21-cm results are concerned, there is nothing new to report. The most reliable results are those of Penzias and Scott (1968) $n_H/T_E < 1.8 \times 10^{-8}$. Field (1972) concludes that $T_E \simeq 18$ K, so that $n_H < 3.2 \times 10^{-7}$ cm^{-3}, compared with a critical value of 2.8×10^{-6} cm^{-3}. The limit based on the absence of a step longward of 1420 MHz, which would be due to intergalactic emission, is a weaker one and is about 4.7×10^{-6} cm^{-3}. These results suggest that the neutral gas, smoothly distributed, can at most be about 10 times the mass in galaxies. A value close to this would imply a value of $q_0 \simeq 0.2$, which is certainly not ruled out when the real uncertainties associated with the attempts to determine q_0 by the direct method are evaluated. I stress this result because it is the most certain upper limit to the density of either neutral or ionized gas in the cosmos.

We turn next to the method based on the attempts to detect Lα absorption in the spectra of QSOs with redshifts $\gtrsim 1.8$. I shall not repeat a discussion of the history of these attempts which have been described elsewhere (Burbidge and Burbidge, 1967; Burbidge and Burbidge, 1969; Bahcall, 1971). No evidence of an absorption trough in a QSO attributable to Lα extending from the blue wing of Lα emission to the atmospheric cut-off has ever been found, though a very large number of QSOs with large redshifts have by now been studied. As was stated in my previous review, either this means that the QSOs are not at cosmological distances, and this question is being discussed by Arp (p. 199) and Sargent (p. 195) at this conference, or the gas which is smoothly distributed is highly ionized. There is also the very remote possibility, discounted by almost everyone, that the space between the galaxies is essentially devoid of gaseous matter, $n(z \simeq 2) \leqslant 1.5 \times 10^{-11}$ cm^{-3}, so that all of the matter is condensed into discrete objects.

As is well known, I consider it very likely that the QSOs are comparatively close by, and if this is true we can get no information about the presence or absence of intergalactic gas from studying them. However, the majority has not yet accepted this view, and the absence of the Lα trough marked the beginning of the many studies in which it was argued that the intergalactic gas must be very hot. We shall describe the evidence bearing on this possibility later.

What if the gas in intergalactic space is condensed into clouds? In this case, there is the possibility that the absorption spectra of typical clouds could be detected in the spectra of cosmologically distant QSOs.

It is well known that many QSOs with very large emission-line redshifts have rich absorption-line spectra. Since 1966 the question has been asked whether the absorption features arise in, or very close to the objects themselves, or whether they arise in the intervening medium. In addition to the optical observations, very recently Brown and Roberts (1973) have detected the first example of 21-cm absorption in the radio spectrum of a QSO. The object is 3C 286 which has an optical emission-line redshift $z \simeq 0.85$ while the absorption feature, if it has a rest wavelength of 21 cm, has a redshift of 0.69. In what follows I am borrowing heavily from a recent study (Burbidge and Burbidge, 1974) in which full references are given.

The general characteristics of the optical absorption spectra are:

(i) The majority of the absorption redshifts are very close to but less than the emission redshifts. However, some are very different.

(ii) The QSOs with absorption lines tend to have multiple absorption-line redshifts.

(iii) Many of the absorption lines are exceedingly sharp; in the case of PHL 957 the line widths are $\lesssim 30$ km s^{-1}, and the width of the 21-cm line in 3C 286 is less than 8.2 km s^{-1}.

(iv) In some objects, notably PHL 5200 and PHL 957, there are very broad absorption features. In them line widths of ~ 200 Å are found.

(v) There is considerable evidence that different redshift systems in some QSOs are connected by a line-locking mechanism suggesting that shells of gas are ejected from the QSOs by radiation pressure.

The two recently discovered QSOs with very large redshifts, OH 471 (Carswell and Strittmatter, 1973) and OQ 172 (Wampler *et al.*, 1973) ($z = 3.41$ and 3.53, respectively) have rather different spectra. OH 471 shows comparatively weak absorption, but a sharp cut-off in radiation shortward of the Lyman limit, while OQ 172 shows very many (>130) sharp absorption lines, and considerable radiation beyond the Lyman limit. Since these objects have very similar redshifts, it would be hard to attribute the differences in the absorption spectra and the behaviour at the Lyman limit to the effects of an external intergalactic medium. It is more likely intrinsic. As far as the absorption spectra in general are concerned, we now summarize the arguments for the idea that they are due to intergalactic gas, and then for the idea that they arise in the QSOs themselves.

The arguments can be divided into two classes: General (statistical, etc.) and Detailed (individual objects; spectroscopic details).

6.1.1. *General Arguments*

In Favour of an Intervening Galaxy or Cloud

(a) If QSO redshifts are cosmological, one would expect that the line of sight to distant objects might intersect one or more intervening galaxies or intergalactic clouds if they exist.

(b) The absorption lines seen, for example, in PHL 938 are those predicted by Wagoner (1967) to appear if the absorption takes place in an intervening galaxy.

(c) The higher the redshift, the better the chance of seeing intervening absorption, and it is indeed the objects with $z \gtrsim 2$ which predominantly show absorption.

In Favour of QSO Production

(d) A histogram of distribution of $(z_{em} - z_{abs})$ shows a peak close to zero, meaning that most have $z_{em} \approx z_{abs}$. In a number of cases $z_{abs} > z_{em}$. These results strongly suggest that absorption lines are produced by gas in association with the QSO.

(e) If the emission redshifts are cosmological, we would expect, statistically, that all high-redshift QSOs would have one or several sets of absorption lines. In fact, it is found that (i) there are several objects having 5–8 sets of absorption lines; (ii) there are still some well-examined cases of objects with no absorption lines; (iii) there are objects such as 4C 5.34 and OQ 172 with a few sets of absorption lines, plus a large number of lines which appear to be only Lα, or Lα and Lβ. On the 'intervening cloud' theory, this would require the existence of dozens of clouds strung out between object and observer, spanning a large distance in some cases and none in others.

(f) The very broad absorption features in PHL 5200 (which is so far unique) are clearly associated with the object. Signs of incipient break-up of the broad absorption into multiple absorption suggests a sequence of events: ejection of optically thick gas at a range of velocities, 0–10^4 km s^{-1}; acceleration of some of the gas; onset of instability of gas leading to filament formation; stabilization of regions through which ions flow at particular velocities. These events can be understood in terms of a model with ejection followed by radiative acceleration and stabilization through gravity. An alternative model could be developed in which it is supposed that the gas shells lie at different levels in a gravitational potential well, with radiative balance.

Points (d), (e) and (f) appear to be quite definite in indicating that the absorptions are intrinsic to the QSOs. Several lines of observational investigation are suggested. They include:

Determining the smallest absorption redshift from the Lyman lines in 4C 5.34. The largest absorption redshift is very close to the emission redshift, $z = 2.88$. Can lines identifiable as Lα extend to the observational cut-off, i.e., to $\lambda = 3200$ Å? If so, they would extend to $z \approx 1.6$, and this would conclusively rule out the 'intervening cloud' hypothesis. How far do they extend in OQ 172, which has an even larger z_{em} of 3.5?

Deciding how many of the unidentified lines in the rich multiple absorption line objects such as PKS 0237-23 and PHL 957 are Lα, or Lα and Lβ.

Looking for secular changes in the spectrum of PHL 5200.

We now turn to more detailed arguments.

6.1.2. *Detailed Arguments*

In Favour of Intervening Galaxy or Cloud

(a) There is only one QSO for which the spectroscopic detail might be said to support the 'intervening' cloud hypothesis. It is PHL 938. However, even in this case, there are counter-arguments. We have already mentioned that the lines seen in PHL 938 were those predicted by Wagoner. The most cogent argument is that the Fe II lines at $z = 0.613$ come from several multiplets, and only those arising from the zero energy states are seen. None are present from the fine structure states at $z = 0.05$–0.11 eV. This means low-density gas, far enough removed from energy sources of UV or IR radiation not to have detectable population (cf. Bahcall and Wolf, 1968).

Against Intervening Galaxy or Cloud

(b) PHL 938 is a multiple-absorption object in having $z_{abs} = 1.906$ and 0.613, even though the former shows only Lα.

(c) PHL 938 may have yet another system at $z = 1.4$. Detailed comparison of its Fe II lines with satellite UV observations of stars shows that there are two unidentified lines in among the Fe II group around $\lambda = 3800$ Å in PHL 938. These fit very well with C IV $\lambda\lambda$ 1548, 1551 at $z \simeq 1.4$ (the ratio is correct to the 4th decimal place). Could this be a coincidence?

In Favour of QSO Production

(d) All sets of lines in different redshift systems in the multiple-z objects such as PKS 0237-23 are spectroscopically similar.

(e) Such differences as exist, e.g., in 1311+170 (Strittmatter *et al.*, 1973), are explicable in terms of a different radiative flux on the gas.

(f) 3C 191, OQ 172, and probably 1331+170 have excited fine-structure states of Si II populated.

(g) C IV $\lambda\lambda$ 1548, 1551 is a frequent doublet in absorption-line systems, but does not appear in interstellar gas in our Galaxy because the level of ionization required is too high.

(h) Coincidences in the wavelengths of absorption lines (absorption on the violet wing of the emission, one line at one z near-coinciding with a different line at different z) have *no explanation* in the 'intervening' hypothesis, but have a possible explanation (line-locking from radiative-gravity balance) in the QSO production hypothesis.

This has been a brief summary of the observational evidence. Finally, we mention briefly an argument of a semi-theoretical kind.

An argument which has been used against the idea that the absorptions are associated with the QSO is as follows: Studies of the excitation conditions in some cases have led to limits of several tens of kpc or more between the centers of emission in the QSOs and the absorbing clouds (McKee *et al.*, 1973). It is then argued that it is unreasonable to suppose that gas which is ejected can have maintained such a small velocity dispersion so far from the QSO. This argument itself is somewhat circular since it starts off by assuming a high luminosity derived from a cosmological distance whereas, if it is assumed that the QSOs are closer, their intrinsic luminosities are much lower and the radiation incident upon the gas is much less, and so the permissible limits to the distance between gas and source are correspondingly reduced.

A related argument has been made in the case of the 21-cm line in 3C 286, which is then attributed to the outer part of an intervening galaxy (Brown and Roberts, 1973). However, it can be seen from the calculations of Davidson (1972) among others that it is perfectly possible to have fairly dense clouds close to the QSOs and explain the features seen.

To conclude, it seems very unlikely that any of the absorption in the spectra of QSOs is attributable to the presence of an intervening medium.

6.2. Detection of Highly Ionized Gas

The best chance of detecting ionized intergalactic gas would occur if it had a temperature high enough so that it emits thermal bremsstrahlung, with photon energies high enough that they are not appreciably absorbed by gas in our Galaxy. This means photons with energies $\geqslant 0.2$ keV, or gas temperature $\geqslant 2 \times 10^6$ K.

Over the last few years a diffuse X-ray flux has been detected over an energy range from ~ 0.25 keV to a few MeV. Whether any of this flux is thermal bremsstrahlung from hot intergalactic gas is still a matter of dispute. I shall discuss first the soft X-ray flux with energy near 0.25 keV and then the possible origin of the harder X-rays. Field (1972), Felten (1973), and most recently Silk (1973), have surveyed all but the most recent data.

6.2.1. *Possible Origins of the Soft X-Ray Flux*

It seems likely that there are at least two components of the soft X-ray flux, one arising in the Galaxy and the other generated outside. Much attention has been paid to various kinds of discrete source models which could account for the galactic component, but this will not concern us here.

Felten (1973) and Hayakawa (1973) have concluded from a survey of the observations (some of which are in conflict), that the flux arising outside the Galaxy in the direction of the poles ~ 500 photons $(\text{cm}^2 \text{ s sr keV})^{-1}$. It may be a real extragalactic flux coming from great distances. The strongest objection to this hypothesis is the fact that the Wisconsin group (McCammon *et al.*, 1971) have failed to observe absorption of this flux by the Small Magellanic Cloud. Their result suggests either that the flux arises between us and the Clouds, perhaps suggesting a hot halo model but no extensive extragalactic component, or that sources in the SMC fill up the hole caused by absorption of extragalactic flux coming from that direction. This latter proposal does not appear likely, but on the other hand it is difficult to explain all of the other observations without invoking the presence of some extragalactic component. At the same time Kraushaar (1973) has pointed out that, if we accept this explanation, it implies that normal galaxies could explain the whole of the observed background if they radiate at the level required of the Small Magellanic Cloud. Consequently, the extragalactic component would arise in normal galaxies and not in the extragalactic medium. Thus, even if it is present, it does not necessarily imply the existence of hot intergalactic gas. Flux at this level of intensity would be radiation by a hot intergalactic gas distributed uniformly, with $T \sim 4 \times 10^6$ K and a density approximately 0.3 of the critical density, i.e., $n_e = 10^{-6}$ cm^{-3}. Of course, if the sources arise in a superposition of discrete components involving hot gas, perhaps gas in clusters of galaxies (for later discussion), the mean density of the gas will be correspondingly lower. (If the gas only fills 1% of the total volume, the density in this volume must be ~ 3 times the critical density but the mean density will be only 3% of the critical density.) Local models in which it is supposed that the flux arises in a hot halo, or in hot gas in the Local Group ($R \sim 1$ Mpc, $n \approx 3 \times 10^{-4}$ cm^3, $T \simeq 10^6$ K) (Hunt and Sciama, 1972), are also tenable.

With all of the present uncertainties, we see that the soft X-ray flux cannot be taken as a very reliable indicator of the presence of hot intergalactic gas.

6.2.2. *Possible Origins of the X-Ray Background with Photon Energies* $\geqslant 1$ keV

There is no question but that a highly isotropic X-ray flux with photon energy $1\ \text{keV} \leqslant E \leqslant 100$ MeV is present and has a truly extragalactic origin. The only mechanisms which are likely to be responsible for generating this flux are Compton scattering of relativistic electrons on the microwave background radiation, or thermal bremsstrahlung from a very hot gas and, at the high energy end, π° decay. There are several important questions that need to be answered before we can decide how important the X-ray background is from the point of view of studies of intergalactic matter. Not only must we identify the production mechanism, but we must also ask whether the background radiation is likely to be made up of discrete sources of known types.

As far as the mechanism generating the hard photons is concerned, the most important point is the shape of the spectrum. The proposals of Felten and Morrison (1966) and of Brecher and Morrison (1969) were that the Compton scattering of relativistic electrons on the microwave background was likely to be responsible. However, as was pointed out by Cowsik and Kobetich (1972), if there is a sharp enough bend in the spectrum as is perhaps the case near 40 keV, this may be difficult to explain if the relativistic electron spectrum does not have a bend as an intrinsic property. At the same time Brecher (1973) has correctly pointed out that, on the basis of what is presently known about synchrotron radio spectra and their parent electron spectra, the existence of bent electron spectra is not excluded.

On the observational side, it is clear that nothing can be concluded for certain until a very well determined spectrum of the background flux is measured. It still appears possible that there is very little change in the slope between ~ 10 keV and ~ 10 MeV (Pal, 1973; Pinkau, 1973) and, if this is correct, the Compton explanation is adequate and very plausible. However, despite the uncertainties in the data, many theoreticians and observers seem to have largely excluded the Compton explanation and have turned to the thermal bremsstrahlung model.

Field (1972) recently concluded that the present observational data are not too far in disagreement either with a hot gas model (uniform density) in a Friedmann universe (big-bang model) with an intergalactic gas temperature of 2×10^{8} K (assuming $\gamma = \frac{5}{3}$, adiabatic expansion since $z \simeq 1$, and a closure density), or a Gold-Hoyle steady-state model ($T \simeq 6 \times 10^{8}$ K).

More recently, the results summarized by Schwartz and Gursky (1973) modify Field's conclusion and, in terms of a hot gas model in a Friedmann universe, they argue that the density is less than the closure density by a factor $\sim \sqrt{2}$, or that the temperature $\leqslant 3 \times 10^{7}$ K, or that the Hubble constant is only about 50 km s^{-1} Mpc^{-1}.

To summarize, with considerable uncertainty, the existence of the diffuse X-ray background can be adduced to be evidence in favour of the existence of very hot intergalactic gas, but in no sense do the observations prove that such a gas exists.

Even if the radiation is thermal bremsstrahlung, it is possible that the diffuse background is simply a sum of the radiation from discrete sources. We know that various types of extragalactic objects are discrete X-ray sources, though at present only a small sample of different types has been identified. The most prominent discrete sources are rich clusters of galaxies, but an attempt to add up the contributions from normal galaxies, radio galaxies, rich clusters, Seyfert nuclei, and QSOs led Schwartz and Gursky (1973) to the conclusion that they can only explain about 22% of the background from discrete sources, and the bulk of this is due to Seyfert galaxies based on a sample of one, NGC 4151.

6.2.3. *Other Observational Evidence for Gas in Clusters of Galaxies*

It has just been pointed out that a number of rich clusters of galaxies have been identified as extended X-ray sources (cf. Kellogg *et al.*, 1973). They may either be radiating X-rays which are due to Compton scattering, or they may be due to thermal bremsstrahlung, thus indicating the presence of gas in the clusters. Practically all of the clusters which have so far been identified also contain active radio galaxies so that, as was proposed by Brecher and Burbidge (1972b) [see also Burbidge (1973)], Bridle and Feldman (1972) and others, it is natural to suppose that X-rays will be generated through the Compton effect, since both relativistic electrons and the microwave background radiation are present. However, many workers have chosen to argue that the detection of extended X-ray sources indicates the presence of hot gas (cf. Silk, 1973). Attempts have been made to show that there is a correlation between the random motions of the galaxies in a cluster and the X-ray luminosity (Solinger and Tucker, 1972). While much has been made of the correlation $L_X \propto$ (velocity dispersion)^4, I do not find it very convincing since only a very small number of clusters (3 in the first instance) with good velocity dispersions are involved. These clusters are of different physical and dynamical types, while the velocity dispersions are not very different. This is why a correlation can only be found with a high power of Δv. Also theoretical work has been carried out based on the idea that the X-ray sources definitely show that hot gas is present (Yahil and Ostriker, 1973).

In fact, in my view, for the X-ray sources in clusters in general, no conclusion as to which mechanism is operating can yet be drawn. The best way of deciding this question is through studies of the X-ray spectra and measurements of the angular sizes and intensity profiles of the sources. In the simplest models we might expect that the Compton X-rays would have a spectrum of the form $I(E) \propto E^{-\alpha}$, while an exponential form with a single temperature would be expected if the X-rays are thermal bremsstrahlung. In more realistic models we expect considerable departures from these conditions. The problem encountered by some groups in handling the Gaunt factor (cf. Margon, 1973) has compounded the difficulties in interpretation. The majority of the clusters have been detected by the UHURU satellite and, in a recent paper, Kellogg *et al.* (1973) have shown that there is a wide range of X-ray luminosities and that either mechanism can be accommodated. The most closely studied cluster is the Coma cluster. In its central part a soft X-ray source ($E_X \leqslant 2$ keV) has been discovered (Gorenstein *et al.*, 1973). The spectral data from these measurements together with the higher energy measurements suggest an exponential spectrum rather than an inverse power-law form. Gorenstein *et al.* therefore argue that the radiation most likely arises in a hot gas with $T \simeq 10^8$ K, $\varrho \simeq 10^{-27}$ g cm^{-3}. Even assuming a uniform density, the total mass of gas is far less than that required to bind the cluster.

The general conclusion from the data available on X-ray emission from clusters is that evidence for the presence of gas is ambiguous, but even if hot gas is present, it only contributes a small fraction of the total mass if the clusters are gravitationally stable.

Another approach to the problem of the existence of intergalactic or intracluster gas is through the study of extragalactic radio sources. Sources which have been identified with optical galaxies both inside and outside clusters frequently have two major components (which are structured) centred about the optical system. They have clearly been ejected from the parent galaxy and, since they have not freely expanded, they have either been contained by the pressure of an external medium or the components must contain enough mass to hold themselves together. A critical account of the various schemes which have been proposed has recently been given (De Young and Burbidge, 1973). Many authors who favour the ram-jet mechanism feel that the fact that it can explain some features of the sources is evidence for the existence of intergalactic gas, and with a judicious choice of parameters it has sometimes been claimed that the gas present is adequate to bind clusters or to equal the critical cosmological density. In fact, there is great uncertainty in these quantities and, if one goes to a model in which it is argued that the sources are generated from a number of coherent objects which are ejected from the galaxy, very little, if any, gas is required.

Further arguments along somewhat similar lines have been made following the studies of radio sources which appear to consist of active galaxies with radio trails (Miley *et al.*, 1972; Miley, 1973; Wellington *et al.*, 1973). Since these observations have only so far been interpreted by those who have used the observations on the *assumption* that an intergalactic medium is causing the effects observed, it is difficult to decide at this stage whether or not the results provide unambiguous evidence for the presence of gas.

Another line of evidence which also remains somewhat ambiguous is concerned with the high latitude 21-cm observations which have been interpreted by Oort (1971) as evidence that intergalactic gas is being accreted by the Galaxy. Other interpretations have been proposed, the most plausible of which is that this gas has been ejected from the Galaxy and is now falling back in.

Finally, we describe briefly evidence that gas is likely to be present following the evolution of galaxies.

If galaxies are formed by a process of condensation from a lower density medium, it is to be expected that some intergalactic gas is left behind. For those who are quite certain that galaxies formed by condensation, this provides the primary reason for believing in the existence of intergalactic gas. Oort (1970) has argued that only a small fraction ($\sim 1/16$) of the mass will condense into galaxies, leading to the view that 15/16, or approximately the closure density, is present in intergalactic gas. For the minority, including Ambartsumian, Hoyle and Narlikar, who believe that galaxies have evolved from very high density states, this cosmogonical argument for the presence of much intergalactic gas is hardly convincing.

Given that galaxies are indeed present, there are a number of processes which we know are operating which will tend to expel gas from them into the outside medium. These include:

(i) Large-scale explosions in the nuclear regions which are able to eject large masses at velocities considerably in excess of the escape velocity (cf. Burbidge, 1970).

(ii) Processes involving galactic winds (Mathews and Baker, 1971) which will drive gas from galaxies and eventually from clusters. Within clusters it is therefore reasonable to suppose that gas is present which has been ejected from galaxies and heated by the passage of other galaxies (Ruderman and Spiegel, 1971). If gas were present outside clusters, the converse process of accretion might occur (Gott and Gunn, 1972).

However, if the gas which is present in the intergalactic medium is only that which has been ejected from galaxies, it follows that the total mass involved is likely to be very much less than that presently condensed into galaxies, so that it will not approach the critical density.

7. Discrete Objects

It appears likely that there could still be much mass in the Universe in the form of dark discrete objects which have so far remained undetectable. This possibility has been discussed before by me and by others, and there is very little new that one can add. If some clusters of galaxies (like the Coma cluster) are bound, it is likely that this mass is in the form of evolved galaxies, dwarf systems, black holes or white holes.

Press and Gunn (1973) have recently discussed the possibility that, if the number of such objects is high enough (close to the critical density), it may be possible to detect them by the method of gravitational imaging.

8. Conclusions

There is still no very good direct evidence for the presence of significant amounts of mass-energy in forms other than that of discrete luminous objects, namely galaxies. Some intergalactic diffuse matter is likely to be present, but no strong evidence is available that its density approaches the critical value. My own view is that it is most likely that a significant amount of cold intergalactic hydrogen is present. As was stated earlier, if the quasi-stellar objects are comparatively close by, no limits are placed on the density of intergalactic gas from their absorption spectra, and the limit set by Penzias and Scott (1968) allows us to assume that quite a large mass – much greater than that in the galaxies – is present in the form of cold gas. It is also possible that we live in a universe in which $\varrho \ll \varrho_c$. Alternatively, as is well known, we cannot exclude the possibility that the bulk of the mass-energy is present in such exotic forms as neutrinos or black holes.

The X-ray observers should perhaps be discouraged from feeling that they ought to find evidence for large amounts of hot gas – it may simply not be there.

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DISCUSSION

G. de Vaucouleurs: May I point out that this so-called average density of the Universe in the form of galaxies is a traditional fiction. One always gets the same number because the same galaxy counts to about the same faintest limit ($19 < m < 21$) are used over and over again so we are always dealing with the same volume of space. It does not prove that we are reaching a significant constant of universal value. Deeper galaxy counts ($m > 21$) are needed, with appropriate corrections, for a definite solution of this problem.

G. Burbidge: I have no comment on this point – perhaps Professor Oort would like to take it up?

Oort: In answer to the doubt expressed by de Vaucouleurs whether we can get any sensible estimate of the general density in the Universe furnished by galaxies, I would remark that in the first place one can get information on the luminosity function of galaxies from observations in nearby clusters. In the second place, the fact that we find approximate isotropy in the distribution of galaxies and clusters of galaxies if we go out to about 10^3 Mpc distance indicates that the volume surveyed is representative of the Universe as a whole (i.e. that in such a volume we have evened out the largest-size irregularities in the Universe).

G. de Vaucouleurs: Unfortunately the deepest galaxy counts to a well-calibrated limiting magnitude ($m = 19$, the Lick Survey) reach out to 200–300 Mpc only, which is not much larger than the scale of the largest size-irregularities so far detected (the Kiang-Saslaw analysis of the Abell clusters). Until much deeper counts are available the evidence that we have indeed reached a plateau of constant density in the $\log \varrho$–$\log R$ relation is subject to reasonable doubt.

Heidmann: I do not completely agree with de Vaucouleurs about the mean density of the Universe. Deep galaxy surveys lead to a density of a few $\times 10^{-31}$ g cm^{-3}. But this mean density is already reached for a volume within 10 Mpc radius centred on the Earth. This volume is already typical of the Universe at the gigaparsec scale. Of course, if this volume were centred on the Local Supercluster it would yield a higher density, as shown by de Vaucouleurs' density-radius relation.

G. de Vaucouleurs: 10 Mpc is much too small. Why don't you take just the first kiloparsec?

Baldwin: A search we have made at 21 cm (unpublished) suggests that the number density of intergalactic H I clouds is less than 3% of that of known galaxies for masses of $\sim 10^{10}\ M_\odot$, and for masses of $\sim 10^8\ M_\odot$ is certainly no larger than that of known galaxies. For lower masses the absorption measurements of Penzias and Scott (*Astrophys. J. Letters* **153**, L7, 1968) provide the best limits.

Allen: It should be remembered that any emission measurement designed to detect intergalactic neutral hydrogen will fail if the spin temperature of the H I is in equilibrium with the 3 K background; H I at 3 K would be quite invisible in emission. Furthermore, if the gas is condensed into clouds, then it is possible that the available absorption measurements (on Virgo A, Cygnus A) have simply missed them.

G. de Vaucouleurs: If you take the ratio of hydrogen mass to total mass, or hydrogen mass to total luminosity for galaxies, there is a tendency for the fraction of the mass that is hydrogen to increase toward the later types, reaching an upper limit of about 10%. Why don't we see galaxies with 50%, 75% or even 100% of their mass in hydrogen?

G. Burbidge: I have no ideas about this one. I don't know how to make galaxies – that's my problem.

E. M. Burbidge: What about the compact galaxies which were called 'giant H II regions' by Sargent and Searle – were these not supposed to contain a large amount of neutral hydrogen?

Heidmann: There are extragalactic objects with a relative neutral hydrogen content higher than 10%, e.g. the Zwicky dwarf compact galaxies such as II Zw 40 in which the hydrogen mass is as large as the mass of stars.

G. de Vaucouleurs: How is the total mass obtained?

Heidmann: By a virial theorem estimate.

G. de Vaucouleurs: I don't believe that's reliable.

Toomre: Does Sargent believe such an estimate?

Sargent: Yes. I think the numbers are consistent with the mass fraction of hydrogen in some of these objects being almost 100%.

G. de Vaucouleurs: Only 20 yr ago, people were calculating the mass of the Large Magellanic Cloud by the same method, taking the 20 km s^{-1} width of the 21-cm hydrogen emission line as *the* velocity dispersion. This was complete nonsense because this is just the z velocity dispersion in a flat system, seen nearly face-on. As we know now, most of the kinetic energy is in the rotation; the virial mass is at best a lower limit of the true total mass.

Longair: Despite the wide range of models for the containment of radio source components involving ram pressure, a universal requirement is that $\varrho_e V^2 = U_{\min}$, where ϱ_e is the ambient gas density, V the component velocity and $U_{\min}$ the minimum energy density in the component. It also applies to 'continuous flow' models such as the Rees model. Taking the largest values of $U_{\min}$ found in external radio components, and the maximum permissible values of V, i.e. the velocity of light, gives an absolute lower limit to ϱ_e of the order of the cosmological density. However, there is no guarantee that it refers to the intergalactic gas – rather, in many cases, it must refer to gas in clusters or even the outer regions of radio galaxies.

We have been investigating whether there exist real differences between sources reported to be in clusters and those in the general field and, whilst we have been hampered by the difficulty of distinguishing when a source is in a group or cluster, we find no evidence for any difference in the properties of double sources inside and outside rich clusters. I make a plea to the experts to help distinguish what types of clusters are associated with powerful radio sources since the data are at present extremely inhomogeneous.

G. de Vaucouleurs: One of our students at Texas, Mr F. Owen (now at NRAO), has been looking at radio sources in Abell clusters and his results, interpreted on the ram-pressure model, indicate that the density in the intergalactic medium decreases outwards from the centres of the clusters.

Longair: We obtain the opposite. When care is taken to avoid selection effects, there are no significant differences between sources in and out of clusters.

Kellermann: Is there any missing mass? Why should we worry about the critical density at all?

G. Burbidge: Why indeed?

Peebles: We can form, from Hubble's constant H and Newton's gravitation constant G, a number with units of density, H^2/G, and it seems a wonderful coincidence, and perhaps deeply significant, that the mean mass density of galaxies is roughly similar to this number. Of course one would like to see how close the coincidence is. Beyond this the 'critical cosmological mass density' is mainly theological.

Conway: The measurements of linear polarization in quasars and its fall-off at long wavelength, if interpreted as due to the Faraday effect, give values for the electron density within the components of the source. On the ram-pressure model one can give corresponding values *outside* the source, and these values come close to $5 \times 10^{-30} (1 + z)^3$ g cm^{-3}, i.e. close to the closure density. Of course, if the quasars are really in distant clusters of galaxies, this value is the cluster density.

Baldwin: Measurements of radio sources with steep spectra, associated with X-ray sources in clusters of galaxies, have shown them to be of relatively small angular sizes. This suggests that the origin of the X-rays is more likely to be a thermal mechanism than the inverse Compton process and puts a lower limit on the density of hot gas.

Gott: It is interesting that clusters like the Coma cluster contain such a small amount of hot intracluster gas. In reasonable cosmological models, material around the outskirts of the cluster should be bound to it and suffer infall into the cluster. Calculations show that, if $q_0 = \frac{1}{2}$ and if the missing density is supplied by intergalactic gas, then one would have expected more gas to have accumulated by now in the Coma Cluster than is actually observed. This argues against the presence of a closure density of intergalactic gas.