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The formation of dark matter in cooling flows

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SUMMARY

We propose that the unseen baryonic matter required by standard nucleosynthesis models is in the form of low-mass stars formed in cooling flows. We motivate this hypothesis by considering a hierarchical model for the formation of structure. Feedback of supernova energy limits the amount of star formation with a normal initial mass function (IMF), so that less than a half of the baryons are locked up in stars at the epoch of giant-galaxy formation. At later stages, when the ratio of the cooling time to the free-fall time of the gas in haloes exceeds unity, we suppose that the IMF becomes biased to low-mass stars, as in current-day cooling flows. Baryonic dark matter then dominates luminous matter in the largest galaxies, groups and clusters. The model explains the widespread occurrence of dark matter in these objects. It also reproduces the observed metal abundance of the intracluster medium and makes a number of other observational predictions. One of these, the copious soft X-ray emission produced by the cooling gas, can give fluxes detectable by *ROSAT*.

1 INTRODUCTION

Standard primordial nucleosynthesis models have been effective in explaining the relative abundances of light elements in the Universe provided that the baryonic mass density is in the range $0.011 \lesssim \Omega_b h^2 \lesssim 0.048$ (e.g. Yang *et al.* 1984), where the Hubble constant $H_0 = 100\ h$ km s^{-1} Mpc^{-1}. The observed V luminosity density in the Universe is $(1.7 \pm 0.6) \times 10^8\ h\ L_\odot$ Mpc^{-3} (Binney & Tremaine 1987, p. 617) which, if due to stars such as those found in elliptical galaxies with a 'normal' initial mass function (IMF) and mass-to-light ratio $M/L \approx (10\text{–}20)\ h\ M_\odot/L_\odot$ (Binney & Tremaine 1987, p. 231), corresponds to a total-mass density in normal stars of $\Omega_* \approx 0.004\text{–}0.017$. Stars in late-type galaxies have smaller mass-light ratios than we have used here, which causes the above value of Ω_* to be overestimated. Clearly all the baryonic matter required by nucleosynthesis models can be in the form of normal Population II stars only if $h \approx 1$ and their density is at the high end of the observed values. More reasonably, if we use the mid-points of the allowed ranges, then $\Omega_* \approx 0.01$ and $\Omega_b \approx 0.05$ with a substantial baryonic dark-matter component.

What form are the dark baryons in? Some fraction will remain as a uniform intergalactic medium (IGM) because galaxy formation is unlikely to be 100 per cent efficient. The Gunn–Peterson test limits the density of cold, H I gas to be (now) less than 1.7×10^{-13} cm^{-3} (Steidel & Sargent 1987), which means that the IGM is highly ionized. Direct evidence for a hot IGM is lacking, especially since recent results from the Cosmic Background Explorer have ruled it out as the source of the X-ray background (Mather *et al.* 1990).

We investigate here the possibility that a significant fraction of the missing baryons is associated with galaxies and is in the form of dark, low-mass stars, created during galaxy formation. The observable consequences of the first population of stars (Population III) have been studied by Carr, Bond & Arnett (1984), who concluded that the only allowed sources of compact objects were either remnants of a very early generation of massive stars ($M \gtrsim 200\ M_\odot$) or low-mass ($M \lesssim 0.2\ M_\odot$) stars and brown dwarfs. It is this latter option that we study here.

There is much evidence for dark matter associated with massive galaxies and especially with groups and clusters of galaxies. Low-mass stars are inferred to form from the cooling intracluster gas found in the cores of clusters of galaxies (for reviews see Fabian, Nulsen & Canizares 1984 and Sarazin 1986). It is the similarity between the conditions in this cooling gas and those in dissipational galaxy formation that motivates us to consider the process in a more universal sense.

We postulate that a substantial fraction of the baryons in the Universe are locked up in low-mass stars which have been produced in cooling flows. (Henceforth the term 'low-mass stars' will be used to mean a population of sub-solar-mass stars, brown dwarfs and/or jupiters, of high M/L.) The implications of nearby cooling flows for galaxy formation and the formation of dark matter have previously been explored by Fabian *et al.* (1986a), Fabian, Arnaud & Thomas (1987), Ashman & Carr (1988), Thomas (1988), Valentijn (1988) and Ashman (1989). The evidence in favour of this view is presented in Section 2, and a model of the process is developed. There are many observable consequences, in particular the soft X-ray emission from the cooling gas, which can be tested in the near future. These are discussed in Section 3. Finally in Section 4 we summarize our conclusions and discuss the results.

2 THE MODEL

2.1 General discussion

A cooling flow is characterized by the inflow of hot gas due to cooling in a potential well in which $t_{\rm dyn} < t_{\rm cool} < t_{\rm H}$, the dynamical, cooling and Hubble times, respectively. In observed flows $t_{\rm dyn} \ll t_{\rm cool} \ll t_{\rm H}$ in the inner regions ($\sim 10-100$ kpc). The main driving force for the inflow is the weight of the outer gas.

Cooling flows have now been seen in at least 70 per cent of nearby clusters (Arnaud 1988; Pesce *et al.* 1990; Stewart, Edge & Fabian 1990) at rates of between 10 and 500 $M_\odot$ yr^{-1}. The minority of clusters which do not contain dense cooling gas are generally those such as the Coma cluster which contain a pair of supergiant ellipticals in their cores, suggesting disruption of the flow by a recent merger (Stewart *et al.* 1984; McGlynn & Fabian 1984).

Although it is well-established that mass deposition is occurring at a high rate in many cooling flows, only a small fraction of this material (at most 10 per cent) is forming stars with a 'normal' IMF appropriate for the solar neighbourhood (e.g. Fabian 1990). We thus have direct evidence of the formation of low-mass stars. Star formation in cooling flows may differ from that in the local ISM since most of the gas in a cooling flow is supported against radial infall by thermal pressure, not galactic rotation. This pressure is high and lowers the Jeans mass of a gas cloud as $P^{-0.5} T^2$. A higher pressure then leads to lower fragmentation masses (Jura 1977; Fabian, Nulsen & Canizares 1982; Sarazin & O'Connell 1983). It is unclear, however, how large a role the fragmentation mass plays in the final distribution of star masses and so the chain of argument is weak. An alternative physical process occurring in cooling flow conditions is the shredding of overdense (cooling) clouds as they fall through the background flow. This has been carefully examined by Nulsen (1986) who concluded that shredding will be effective until the overdensities become small enough to be 'pinned' to the background flow. Large gas clouds are thereby broken into smaller clouds of maximum mass a few solar masses. The large molecular clouds characteristic of massive-star formation in spiral galaxies cannot therefore exist at large radii in a cooling flow. We presume that the upper mass cut-off of the IMF is then reduced relative to that in less dynamic environments such as those in our own Galaxy (Fabian 1990).

Observed cooling flows, even if active for a Hubble time, can only process a small fraction of baryons if their mass-deposition rates are constant with time. If our hypothesis is true, then there must have been a period of more violent activity in the past. We require that the process of galaxy formation resembled a giant cooling flow, in which much of the protogalactic gas was heated to the virial temperature and then cooled slowly in an inhomogeneous manner (an earlier, simple discussion of this is given by Fabian *et al.* 1986a).

The importance of the role of cooling in galaxy formation has been discussed many times in the past, from the work of Gold & Hoyle (1958) and Fish (1964) to the more recent studies by Rees & Ostriker (1977) and of Silk (1977). These last studies emphasize the similarity between the gross properties (mass and radius) of the largest galaxies, and of model, spherical 'top-hat' perturbations in the early Universe which have equal cooling and dynamical (free-fall) times. They do not clearly set out what happens to initial perturbations which do not satisfy that condition. That is the point of our work.

The behaviour of hot gas clouds (the 'protogalaxies') is summarized in diagrams such as Fig. 1(a), adapted from the work of Rees & Ostriker (1977; here we use the cooling curve approximation of Thomas 1988). The exact position and shape of the lines in the diagram depend upon the amount of non-baryonic dark matter and the metallicity of the gas, but we mention the following general points: the region (C), below the solid line, has

$$\frac{t_{\rm cool}}{t_{\rm dyn}} = \tau < 1.$$

This is where normal stars form and it is in this part of the diagram that clouds of galactic mass lie. The cooling flows discussed here occur in region B, between the dashed line, where $t_{\rm cool} = 10^{10}$ yr, and the solid line.

If clouds are small enough, they fall in a region with $T < 10^4$ K, not shown in Fig. 1(a), which also satisfies the condition $\tau > 1$ necessary for a cooling flow. Such pregalactic cooling flows have been investigated by Ashman & Carr (1988) and by Ashman (1989), who suggest that dark clusters of low-mass stars (similar to globular clusters) may form at high redshift, $z \gtrsim 30$. It is difficult, however, to process a large fraction of baryons in this manner (Ashman & Carr, private communication) as the $\tau = 1$ boundary is crossed fairly rapidly. More promising is the transition concentrated on by previous workers and shown in Fig. 1(a). This occurs on the mass-scale of giant elliptical or spiral galaxies (Fig. 1b) and lends credence to the view that the transition from $\tau > 1$ to $\tau < 1$ controls the physics of luminous star formation. It is generally interpreted as marking the cessation of the formation of compact objects such as stars (at least until a cooling time has passed); we view it as a change from high- to low-mass star formation.

We assume that a present-day object represents the end-point of a process of hierarchical collapse. For a massive galaxy, the subunits have increased in mass from region C to region B. At each stage, the gas taking part is heated by gravitational-energy release, and by supernova energy if 'normal' stars were formed at the previous stage. There will also be turbulence and mixing of the enriched material. These and other processes (e.g. active galaxies) acting early in the hierarchy lead to an increasing range of densities in the gas at later stages. Such a range of densities is inferred in present-day cluster cooling flows. Cooling of the denser clumps proceeds continuously and in a spatially distributed manner throughout a hot halo of gas in region B. The hot halo surrounds a 'normal' galaxy (or galaxies) formed earlier in the hierarchy. In our model, it is the baryonic dark halo that forms last.

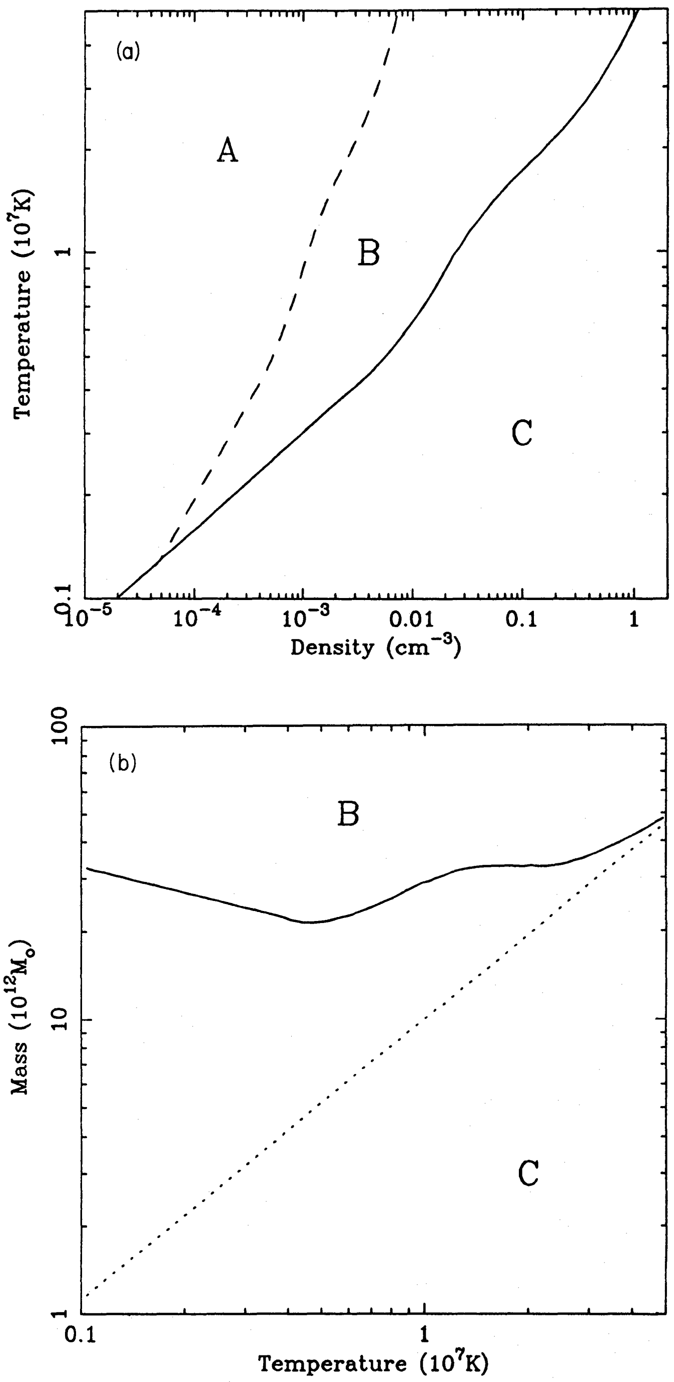

Figure 1. (a) Cooling diagram adapted from work of Rees & Ostriker (1977) and Silk (1977). The solid line corresponds to $\tau=1$, the dashed line to $t_{\mathrm{cool}}>10^{10}$ yr. Cooling flows depositing low-mass stars occur in region B, where $\tau>1$. Normal-star formation takes place in region C, where $\tau>1$. (b) $\tau=1$ boundary in the mass–temperature plane. Cooling flows occur in region B. $Z=0.3Z_\odot$. If $Z=0$, then the $\tau=1$ boundary is the dotted line.

The rate of mass deposition in cooling flows will be greatest near $\tau=1$, i.e. during the formation of giant elliptical galaxies and groups of galaxies. Perturbations on the scale of clusters are now in region A (where $t_{\mathrm{cool}}>10^{10}$ yr) or B – steady cooling flows exist near cluster cores but these and future flows will deposit only a small fraction of Ω_{b}. This picture agrees with observations which show mass-deposition rates of 10–500 $M_\odot$ yr^{-1} in nearby clusters. We assume that small-scale inhomogeneities in the cooling gas lead to widespread mass deposition; in nearby flows $\dot{M}(<r)\propto r$ (Thomas, Fabian & Nulsen 1987), so that the low-mass stars create a roughly isothermal dark halo.

2.2 Relative abundances of luminous and dark stars

One problem which will concern us is the efficiency of star formation. Why do only a small fraction of the baryons form visible stars when $\tau<1$ and yet we are suggesting almost all the remainder do so efficiently when $\tau>1$? The answer to this puzzle may lie in the feedback of energy into the gas via supernovae. This will cause heating and limit the amount of cooled gas in galaxies with normal-star formation. When the transition to low-mass star formation occurs, on the other hand, the feedback will be removed and the gas will cool efficiently.

The influence of supernovae on the gas content and metal enrichment of galaxies has been well-discussed since the work of Larson (1974 – see also Larson & Dinerstein 1975; Mathews 1989 and references therein). We give a simplified version here emphasizing the connection between energy liberated as heat, and metals produced.

We assume that the energy return from the Type II supernovae is instantaneous and is well mixed with the residual gas. The fraction of baryons which can form stars is limited by the associated heating. For the most massive haloes (where $\tau\gtrsim 1$), this will prevent further cooling – any gas which is heated above the virial temperature will be ejected from the halo. We assume that the same would be true for smaller haloes but note that, if the supernova energy is effectively thermalized, then the gas may be able to cool before escaping.

We estimate the energy and metal output of supernovae from results presented in the review by Woosley & Weaver (1986). Type II supernovae are caused by explosions of massive stars, $M\gtrsim 8$ $M_\odot$, and supply 3–4×10^{50} erg of kinetic energy to the interstellar medium. This can heat $85T_7^{-1}$ $M_\odot$ to 10^7T_7 K. The heavy metals are supplied by supernovae in the range 20–30 $M_\odot$ which return most of their mass to the interstellar medium (ISM) when they explode. The mean overabundance in the ejecta, compared to solar values, is about 9, so that one of these supernovae enriches 200 $M_\odot$ of ISM to solar abundance. Taking an IMF of $dN=\xi(\log M/M_\odot)\,d(\log M/M_\odot)$, where $\xi(x)=A\exp[-1.15(1+x)^2]$ (Miller & Scalo 1979), we find that about 0.1 supernovae occur in the mass interval 20–30 $M_\odot$ compared to the total number with $M>8$ $M_\odot$. Thus heating the ISM to 10^7 T_7 K corresponds to a heavy-metal enrichment ≈ 0.24 T_7 solar.

The virial temperature of the massive haloes in which the dark matter forms (see Section 2.3) is in the range 3×10^6–10^7 K. The gas is heated to this temperature during the collapse and must be supplied with an equivalent amount of energy in order to escape (assuming $T_{\mathrm{escape}}\sim 2T_{\mathrm{virial}}$). This gives a metallicity of 0.1–$0.3Z_\odot$. Observations of the metallicity of the intracluster medium in groups and large clusters, based on the iron complex at ~6.8 keV, give values at the upper end of this range (Rothenflug & Arnaud 1986; Edge 1989), which is very strong evidence that feedback from supernovae limits the amount of star formation. (This does not necessarily imply, of course, that low-mass star formation takes over at higher virial temperatures. The more usual view is that star formation ceases altogether in these regions.) If some of the supernova energy is radiated and does not go into heating the gas, then more supernovae are required, thus raising the metallicity. In passing, we note that massive supernovae should overproduce oxygen relative to solar abundance values, in agreement with X-ray line-emission studies (Canizares, Markert & Donahue 1988).

We can also estimate the fraction of baryons which remain locked-up in stars. Using the above Miller-Scalo IMF and taking an upper cut-off of 1 $M_\odot$ for the stars which retain their gas, we find $\sim 80\ M_\odot$ of low-mass stars is associated with each supernova (i.e. $\geq 8 M_\odot$ star). The fraction of the baryons which remain trapped in stars is then $\approx (1+T_7^{-1})^{-1}$. This result depends on the low-mass end of the IMF, which is not well-known. For example, some observations suggest that there are few stars formed with masses less than 1 $M_\odot$ in regions of massive-star formation (Güsten & Mezger 1983; Scalo 1986). This considerably reduces the fraction tied-up in normal stars, and is required by our model with $T_7 \sim 1$, below. The high-mass end of the IMF does not appear to vary with position and so the metallicity estimates, given above, are more certain.

These simple arguments show that, if the first stars form with an IMF similar to that determined for the solar neighbourhood, then the remaining gas is enriched by up to $0.3 Z_\odot$ and a highly uncertain fraction of up to one half of the baryons is locked-up in stars. In the hierarchy of collapses which leads to a present-day galaxy, group or cluster, most of the baryons in the earliest, smallest subunits, were ejected with little enrichment. These baryons would have been swept up in the next stage and ejected again, with only a small fraction forming stars or stellar remnants. The mass spectrum of the perturbations giving rise to the hierarchy must be such that the metallicity of the final gas is determined by the last, most massive, subunits.

Within a galaxy, further enrichment can occur from further generations of stars, or, provided that binary stars can form, from Type I supernovae which each eject up to 1 $M_\odot$ in iron (see Matteuci & Vettolani 1988).

2.3 Cooling flow models

In this section we construct some simple models. Let the fraction of cooling gas which forms low-mass stars be $f_\mathrm{d} = [\tau/(1+\tau)]^n$, say. This just represents a transition from 0 at $\tau \ll 1$ to 1 at $\tau \gg 1$. For $0 < n \ll 1$ the transition is very slow; as $n \rightarrow \infty$ it becomes a step function at $\tau = 1$. Were heating from supernova ejecta not important, we might expect $n \approx 1$ because the cooling time of the gas increases as part of it cools and is deposited. However, as we have seen, only a small fraction of the gas can cool for $\tau < 1$ and so the transition will be sharper, $n > 1$. It is probably sufficient to take $f_\mathrm{d}(\tau) = \Theta(\tau - 1)$ where Θ is the Heaviside function. As already discussed, we assume that denser clumps within the initial gas cloud collapse first (the earlier stages of the hierarchy) and at the highest densities to form a population with a 'normal' IMF which gives rise to supernovae that enrich the rest of the gas. These give the 'visible' galaxy (or galaxies if the cloud forms a group), and the 'dark fraction' is determined by f_d.

Our model predicts that all normal galaxies should be composed of stars with a standard IMF. Because the amount of non-baryonic matter contained in galactic haloes is expected to be small in most theories, the variations in mass-to-luminosity ratios which are observed would be due to the different ages of their stellar populations. Luminous galaxies stop forming when the ratio of the cooling to dynamical times in newly formed haloes becomes equal to unity. We next estimate this mass-scale in two different cosmologies:

(1) $\Omega = 1, \qquad 0.01 < \Omega_\mathrm{b} < 0.2,$

(2) $0.01 < \Omega = \Omega_\mathrm{b} < 0.2.$

The first of these is what we shall call the standard cold dark matter picture and bears some comparison with the core-halo picture by White & Rees (1978). (The baryonic dark matter must be 'cold' in order for our bottom-up scenario to be valid.) However, this scenario also holds in the second case. An example of such a theory is the baryon isocurvature model by Peebles (1988).

The mass of gas clouds which have $\tau = 1$ has been discussed in detail by Thomas (1988); we will briefly summarize the results here. To fix the model we take a polytropic equation of state $P \propto \rho^{5/3} \propto T_7^{5/2}$, where P, ρ and T_7 are the pressure, density and temperature (in units of 10^7 K) of the gas. Clouds are also taken to be spherically symmetric and isolated, with zero outer pressure. A more sophisticated treatment, using realistic density and temperature profiles, will alter the results presented here by factors of order unity – a numerical model is probably required to justify more refined assumptions.

The gravitational free-fall time of the bulk of the cloud is $t_\mathrm{grav} \approx 7 \times 10^7 n_\mathrm{b}^{-0.5} F_\mathrm{b}$ yr, where n_b is the baryon number density and $F_\mathrm{b} = \Omega_\mathrm{b}/\Omega$ is the baryon mass fraction. The cooling time of the gas is $t_\mathrm{cool} = n_\mathrm{b}^{-1} C(T_7)$ yr, where $C(T_7)$ is given in Thomas (1988) for a 0.4 solar metallicity gas. We then have $\tau \approx (F_\mathrm{b} n_\mathrm{b})^{-0.5} C\ (T_7)/7 \times 10^7$. The cloud mass, $M_{12} \times 10^{12}\ M_\odot$, central number density and temperature are related by $M_{12} \approx 4.5 n_\mathrm{b}^{-0.5} F_\mathrm{b}^{0.5} T_7^{1.5}$ (Chandrasekhar 1939), so that $\tau \approx M_{12} F_\mathrm{b}^{-1} Q(T_7)/3.2 \times 10^8$ where $Q(T_7) = T_7^{-1.5} C(T_7)$. Q has a maximum at $T_7 \approx 0.5$ and varies only by a factor of 2 in the range 3×10^5–3×10^7 K, so that $\tau \approx M_{12} F_\mathrm{b}^{-1}/30$ is approximately independent of the virial temperature of the largest galaxies (Fig. 1b). In the subsequent evolution of the galaxy only the baryonic mass will dissipate and remain bound while the non-baryonic component is disrupted by merging. Thus the galaxic mass is $M_{12} \times F_\mathrm{b} \approx 30 F_\mathrm{b}^2$.

(i) In model (1), $F_\mathrm{b} = \Omega_\mathrm{b} = 0.01$–$0.2$ and the maximum galactic mass is 3×10^9–$10^{12}\ M_\odot$. This mass range encompasses galaxies having typical luminosities L_* for a normal stellar mass–luminosity ratio and so we identify the $\tau = 1$ transition with the break in the galaxy luminosity function. Higher luminosity galaxies form by merging and are dominated by baryonic dark matter.

The virial temperature of typical large galaxies is $T_7 \approx 0.3$. To obtain the observed metallicity in clusters we then require that either the supernova energy does not efficiently heat the ICM or that metal enrichment from Type I supernovae is important at later times. (The possible overabundance of oxygen in intracluster gas may rule out the latter possibility.)

(ii) Model (2) has $F_\mathrm{b} = 1$ and so predicts a lower mass of $3 \times 10^{13}\ M_\odot$ for objects rich in dark matter (Fig. 1b). The mass fraction of the luminous component is, from the arguments of Section 2.2, at most 1/2. Then, assuming a normal mass-to-light ratio for this component, we obtain an upper galactic luminosity of $L_V \lesssim 10^{12}\ L_\odot$, comparable with the observed luminosity of the largest galaxies. In this model we identify the transition $\tau = 1$ with giant elliptical galaxies, or with groups of galaxies. The largest galaxy or galaxies in a group, which form from the previous mass-scale in the hierarchy, should be less than the transition mass by at most a factor of a few. We predict that there is then little baryonic dark matter in any but the largest galaxies and groups of galaxies, and we require that normal-star formation must cut off sharply at $\tau = 1$, so that larger luminous objects do not form. Since $T_7 \approx 1$ in this model, the normal IMF would have to be truncated at low masses in order that the ratio of dark to luminous matter exceeds unity.

3 OBSERVATIONAL PREDICTIONS

We discuss here some of the observational consequences of our model. One of its strong features is that its predictions can be tested in the near future.

3.1 Massive cooling flows

We predict that rampant low-mass star formation occurs at the epoch of giant-galaxy or group formation when the remaining gas cools. At later stages, a small fraction of this gas remains such that $t_{\rm cool} \approx H^{-1}$ (i.e. the age of the system). X-ray observations of present-day clusters and groups suggest that this fraction is ~ 0.1.

In model (1) we should find massive cooling flows of up to $\sim 1000\ M_\odot\ {\rm yr}^{-1}$ at $z \sim 1$–few (with the exact redshift range depending upon the model parameters). In model (2) the initial cooling flow is much larger, since the mass of baryons is so much greater and $\dot{M} \sim 10^4\ M_\odot\ {\rm yr}^{-1}$. It occurs at moderate to high redshift (i.e. $z \sim 10$) and would not be detectable. However, the mass of gas remaining is in rough inverse proportion to the time, t, since the structure passed above the $\tau = 1$ boundary (i.e. $M_{\rm gas} \propto t^{-1}$). Therefore, the strength of the cooling flow $\dot{M} \propto t^{-2}$. This means that $\dot{M}$ is also $\sim 1000\ M_\odot\ {\rm yr}^{-1}$ at $z \sim 1$.

Spectroscopy of the 'fuzz' around radio-loud quasars gives estimates of the pressure of the surrounding hot gas (Fabian *et al.* 1987; Crawford & Fabian 1989; Forbes *et al.* 1990). The cooling time in the gas is inferred to be short and gives mass-deposition rates of $\gtrsim 1000\ M_\odot\ {\rm yr}^{-1}$ – which is of the required order. Higher-redshift radio galaxies have similar spectra and are probably also surrounded by massive flows (Fabian *et al.* 1986a).

The X-ray telescope to be launched on *ROSAT* will image parts of the X-ray sky to flux levels of better than $F_R = 10^{-14}$ erg cm^{-2} s^{-1} in the 0.1–2.4-keV band, which should allow us to test our results. As an example, we note that a 3000 $M_\odot\ {\rm yr}^{-1}$ flow from 10^7 K yields a luminosity of $\sim 6 \times 10^{44}$ erg s^{-1}. Such a flow deposits $> 10^{13}\ M_\odot$ in a few billion years and should be individually detectable above F_R out to redshifts $z \approx 2$. (Direct detection of such a flux may be complicated if the central galaxy also contains a quasar.)

3.2 Soft X-ray flux

The upper limit to the diffuse soft X-ray background in the carbon-band (~190–250 eV) provides a strong constraint on the total amount of gas cooling from temperatures above 10^6 K. For the limit, we use the estimate by McCammon (1990) of 100 keV cm^{-2} s^{-1} sr^{-1} keV^{-1}, which has been refined from their work (McCammon *et al.* 1976) on a search for absorption by the SMC and takes into account absorption by He I and He II in the galactic H II layer inferred by Reynolds (1989).

We have computed the integrated intensity in the C band from cooling gas using the spectra and cooling curve of Raymond & Smith (1977) for $Z = 0.3 Z_\odot$. The gas is all assumed to cool from the upper temperature at the chosen redshift. The resulting limits on the product $\Omega_{\rm b} h^2$ are shown. They are stronger than the limits placed by Ashman & Carr (1988) and by Fabian & Nulsen (1979) from the intensity of the X-ray background above 1 keV. We see for model (2) that all the dark matter in clusters and groups of galaxies could plausibly have originated from cooling flows from 10^7 K if $\Omega_{\rm clusters} \approx 0.01\, h^2$ (thick curve in Fig. 2), provided that most of the cooling took place at a redshift greater than 4. The value of $\Omega_{\rm cluster}$ is consistent with that estimated from the cluster temperature function of Edge *et al.* (1990), integrated above temperatures of 10^7 K on the assumption that most of the dark matter was formed in subclusters with virial temperatures of $\sim 10^7$ K. The ultraviolet radiation from the cooling gas would ionize the IGM, provided that most of the baryons take part in the cooling. The limit does not exclude model (1) since there the gas cools from the virial temperatures of an L_* galaxy, i.e. $\sim 3 \times 10^6$ K.

McCammon (private communication) estimates that the C-band limit can be reduced by up to an order of magnitude with *ROSAT* observations of the soft X-ray background. In

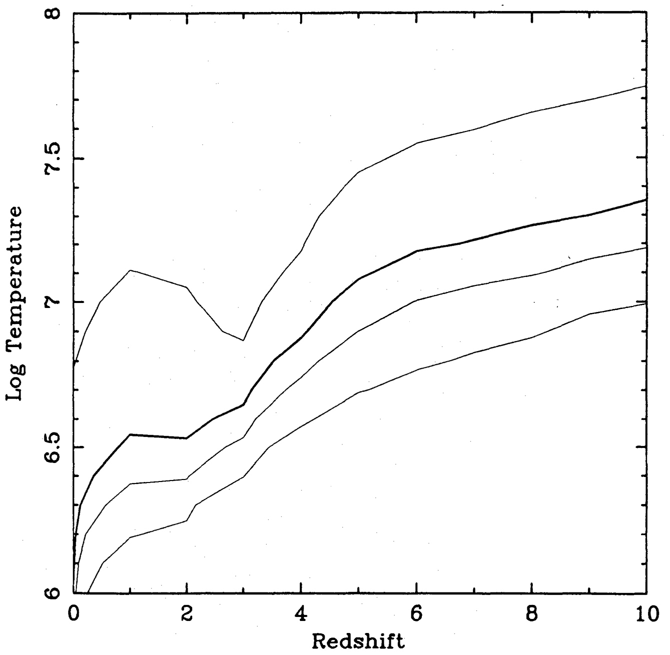

Figure 2. Maximum temperature from which gas at that redshift can cool and emit less than the C-band limit of 100 keV cm^{-2} s^{-1} sr^{-1} keV^{-1}. The amount of gas cooling corresponds to $\Omega h^2 = 0.0025$, 0.01, 0.025 and 0.1 (upper to lower curves). The thick line is appropriate to the dark matter in clusters and groups (see text). If *ROSAT* can achieve a limit of 10 keV cm^{-2} s^{-1} sr^{-1} keV^{-1}, then the curves correspond to $\Omega h^2 = 0.00025$, 0.001, 0.0025 and 0.01.

that case our model is then strongly constrained (or supported). For example, it will either detect or rule out the above simple model for the dark matter in clusters and groups of galaxies. We note that there is sufficient energy in the X-ray flux to ionize the intergalactic medium and in model (2) this could plausibly be the main cause of ionization at high redshifts.

3.3 Mass–luminosity ratios

We predict that most isolated galaxies should be almost entirely composed of 'normal' stars with the mass–luminosity ratio determined by the age, and perhaps the metallicity, of the stellar population. Model (1) departs from this result at high masses ($M > M_*$), with M/L increasing rapidly in the largest galaxies. There is some evidence for this: large values of $M/L \gtrsim 80$ are required in order to bind the hot gas in giant ellipticals (Fabian *et al.* 1986b). Model (2) predicts that dark matter only occurs around the most massive galaxies and in groups and clusters of galaxies. As a consequence, the total mass of the Local Group must exceed $\sim 3 \times 10^{13}\, M_\odot$ if it contains dark matter. Both models allow accretion of dark baryons at late times where the virial temperature is of the same order as the gas temperature.

3.4 Microlensing

Most of the compact objects in group-sized haloes or larger are in the form of low-mass stars. The probability of microlensing is simply proportional to the mass density of compact objects. Thus most microlensing events should be caused by low-mass objects. There is only one microlensing detection so far, although the identification is not certain. From the time-scale of the event the mass of the lens can be estimated as $\lesssim 0.01\, M_\odot$ (Irwin *et al.* 1989) with considerable uncertainty depending upon the transverse velocity of the lens. This result would seem to support our contention.

4 DISCUSSION

We have put forward a model in which most of the unseen baryonic dark matter is in the form of low-mass stars produced in cooling flows. We consider a hierarchy in which low-mass galaxies form first and are populated by stars with a normal IMF. Feedback from supernova heating limits the total amount of gas that can cool. As the hierarchy develops, so the ratio of the cooling time to the dynamical time in gas in haloes increases. We postulate that, when this ratio, τ, exceeds unity (as in nearby cooling flows), few high-mass stars are formed, the feedback from supernovae is terminated, and the residual gas cools efficiently into dark, low-mass stars. If there is other, probably non-baryonic, cold dark matter (such as often inferred if $\Omega = 1$), this process leads to a turn-over in the galaxy luminosity function around L_*, with a substantial baryonic dark matter component in larger systems. Otherwise, all the dark matter is baryonic and is an important component only in objects with masses $\gtrsim 3 \times 10^{13}\, M_\odot$.

Mergers of groups at late times led to the formation of present-day rich clusters, a view supported by recent X-ray evidence for strong cluster evolution (Edge *et al.* 1990). The universal metallicity of cluster gas at $0.3 Z_\odot$ is due to the potential depth of the haloes for which $\tau = 1$, corresponding to $\sim 10^7$ K.

It is possible to estimate simple scaling-laws for the properties of elliptical galaxies in this model. The following argument is similar to, but much less detailed than, that presented in Dekel & Silk (1986) for low-mass galaxies. We suppose that haloes have masses M and radii R when they first virialize. Only a small fraction of the total mass manages to cool and form a galaxy, so the galactic mass is $m < M$. All stars form with the same IMF so the luminosity $l \propto m$. Our model for energy feedback from supernovae implies $m \propto MT$ where $T \propto M/R$ is the virial temperature of the halo. The velocity dispersion of the final galaxy is $\sigma^2 \propto m/R$. Finally we adopt the simple hierarchical model of Kaiser (1986) to determine the relation between M and T, i.e. $T \propto M^{(1-n)/6}$, where n is the power index of the initial fluctuation spectrum. This gives $m \propto M^{(7-n)/6}$ and $l \propto \sigma^{(7-n)/(1-n)}$. In standard CDM this last index varies from 3 to 4 as n varies from -2 to -1 during the epoch of galaxy formation – in agreement with the Faber–Jackson relation (Faber & Jackson 1976). The potential energy $m\sigma^2 \propto m^{3(3-n)/(7-n)}$, giving an index between 5/3 and 3/2 close to that predicted by Fish's Law (Fish 1964). Finally, the metallicity varies as $Z \propto T \propto \sigma \propto m^{(1-n)/(7-n)}$, which gives an index between 1/3 and 1/4. This is slightly lower than the observed index (Dekel & Silk 1986), but is perhaps least well-determined because of the subsequent chemical enrichment which takes place as galaxies evolve.

We suppose that spiral galaxies are formed in a similar manner to ellipticals but with inflow of gas on to the disc at late times. Baryonic dark matter around spiral galaxies is only possible in model (2) if they too occur in groups of total mass above $3 \times 10^{13}\, M_\odot$ The rotational support provided for the disc gas allows large molecular clouds to build up, and leads to continuing formation of massive stars and to their present appearance. The luminous and dark haloes are both baryonic and some 'conspiracy' of light and dark haloes is natural.

The distribution of mass and light in the Universe are not simply related in our model; there is complex 'biasing'. Much of the mass originally associated with low-mass, isolated galaxies is now in the IGM. In the case of groups and clusters, it is now in the form of dark matter. The bias factor is thus a function of the largest scale perturbation that a galaxy belongs to.

The clearest tests of our hypothesis will be obtained from soft X-ray observations. The cooling haloes may be detectable individually as extended soft X-ray sources (perhaps with an active core); the integrated background from galaxy formation may also be detectable by searching for absorption shadows from galactic clouds. The intrinsic anisotropy of the background emission will give important clues to the origin of large-scale structure.

Finally, we note that cooling flow conditions (high-pressure surrounding gas) also occur soon after recombination. If star formation then took place (and we note that Compton processes are very important at that epoch), it could also have taken a low-mass mode.

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