DARK MATTER AND COOLING FLOWS

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ABSTRACT. Cosmological arguments suggest that a large fraction of the baryons in the Universe are dark. Although the background dark matter required to make up the critical density would have to consist of some kind of elementary particle, the dark matter in galactic halos could be baryonic. In particular, we argue that it could consist of jupiters made in pregalactic or protogalactic cooling flows. These would be analagous to the cluster cooling flows observed at the present epoch but on a smaller scale.

1. BARYONIC DARK MATTER

One of the most striking features of the Universe is the prevalence of dark matter: while ordinary visible material has a density $\Omega_v \simeq 0.01$ in units of the critical density, there is evidence that a much larger density is contained in some invisible form (Faber & Gallagher 1979). In fact, there are four contexts in which dark matter seems to arise: (i) there is *local* dark matter, associated with our galactic disk, with a mass comparable to that of the visible disk; (ii) there is dark matter associated with galactic *halos*, with a density parameter of at least $\Omega_h \simeq 0.1$ and possibly more, depending on the (presently uncertain) radius to which the typical halo extends; (iii) there is dark matter in *clusters*, with a density parameter in the range $\Omega_c \simeq 0.2$–0.3; (iv) finally, if one accepts the inflationary scenario, there may have to be unclustered *background* dark matter in order to make the total cosmological density parameter unity.

Some of these dark matter components may be the same. For example, if one believes that individual galaxies are stripped of their halos when they aggregate to form clusters (thereby forming a collective cluster halo), it would be fairly natural to identify (ii) and (iii) providing the original halos were large enough. Likewise (iii) and (iv) could be identified if one invoked some form of biassed galaxy formation in which galaxies form in only a small fraction of the volume of the Universe (Kaiser 1984). On the other hand, it is equally possible that all the dark matter components are different.

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In assessing how much of this dark matter could be baryonic, a crucial constraint comes from cosmological nucleosynthesis arguments (Yang *et al.* 1984). These require that the baryon density parameter lie in the range $0.014h^{-2} \leqslant \Omega_b \leqslant 0.035h^{-2}$ (where h is the Hubble parameter in units of 100 km/s/Mpc). If H_o=100, then the upper limit on Ω_b suggests that only the local dark matter could be baryonic in origin. Thus one would have to invoke some non-baryonic explanation, presumably an elementary particle relic of the early Universe, to explain the rest. On the other hand, if H_o=50 (as seems most likely if one wants the Universe to be old enough to explain the ages of globular clusters), Ω_b could be large enough to explain at least (ii) and possibly (iii). Indeed, if H_o=50, the discrepancy between Ω_b and Ω_v would imply that a large fraction of baryons *must* have gone into some dark form, although the closure dark matter would still need to be non-baryonic.

The suggestion that the halo and possibly cluster dark matter could be baryonic goes against the current trend to assume that all forms of dark matter except (i) are non-baryonic. However, in our view, the arguments advanced in support of this trend (Hegyi & Olive 1986) are not very convincing but just reflect a prejudice that the number of forms of dark matter should be as small as possible. There is really no reason why dark matter should not take on as many different forms as visible matter, so it is no more implausible that baryons should turn into dark material with high efficiency than that they should turn into visible material with high efficiency. Thus the fact that the dark matter required for closure (if such exists) has to be non-baryonic does not exclude the halo dark matter being baryonic. Admittedly, it might seem strange that baryonic material and non-baryonic material should have comparable densities (Turner & Carr 1987) but this is a coincidence which pertains independent of whether or not the baryonic material remains in mainly visible or invisible form.

Although the halo dark matter may in principle be baryonic, it cannot be in the form of ordinary gas else it would generate too many X-rays. The gas must therefore have been converted into some dark form. There are only two ways of doing this: it must have turned into either *jupiters* or the *black hole* remnants of massive stars. Low mass stars seem to be excluded by source counts limits (Gilmore & Hewitt 1983) and other stellar remnants are excluded by nucleosynthesis and background light constraints (McDowell 1986). Carr *et al.* (1984) have argued for the black hole option because of its more dramatic cosmological consequences, but there is no observational evidence that the large stars required can form with the required efficiency (at least at the present epoch). Here we wish to argue for the jupiter option. In particular, we will propose that the jupiters are made in cooling flows, analagous to the cluster cooling flows observed at the present epoch, but occurring at an earlier time and on a smaller scale.

2. COOLING FLOWS AT THE PRESENT EPOCH

Let us first review the evidence for cooling flows at the present epoch. X-ray observations show that many clusters contain hot intracluster gas with a temperature of about 10^8K. In clusters dominated by a central cD galaxy, the emission is peaked at the core, indicating a high central gas density. Since the associated cooling time is less than the Hubble time, one expects the gas in the core to be flowing inwards, driven by the pressure of the surrounding gas, which is too tenuous to cool appreciably. Direct observational evidence for such cooling flows includes the presence of an inverted temperature gradient in cluster cores and the detection via soft X-ray emission of relatively low temperature gas (10^6-10^7K) at the cluster centre. The presence of optical filamentation also provides indirect evidence. The relevant observations have been reviewed by Fabian *et al.* (1984).

The mass flow rate associated with these cooling flows varies from a few $M_\odot\ y^{-1}$ to $10^3\ M_\odot\ y^{-1}$ and it appears that the mass is being deposited over a wide range of radii. Such a high flow rate, persisting over a Hubble time, could in principle provide the mass of the entire cD galaxy. However, if the cooling gas all formed stars with the same IMF as the solar neighbourhood, one would expect the central galaxy to be bluer and brighter than observed. This has led Fabian *et al.* (1982) and Sarazin & O'Connel (1983) to suggest that cooling flows produce lower mass stars than are observed in the solar neighbourhood. Indeed they argue that most of the inflowing gas is turned into some dark form (presumably jupiters). They give a plausibility argument for this, based on the fact that the high pressure in the cooling flow reduces the Jeans mass (assumed to provide an upper limit to the mass of the stars being formed). These arguments are not completely convincing [see, for example, Silk *et al.* 1986] and, in any case, our ignorance about star formation and the origin of the IMF in general should make us wary of any particular explanation for why the stellar mass is reduced in cooling flows. Nevertheless, there does seem to be considerable evidence that such a reduction occurs. The fact that cosmologists have been rather slow to acknowledge this seems to stem from a rather conservative tendency to assume that the solar neighbourhood IMF must apply in all circumstances.

If cooling flows really can produce dark matter with high efficiency, this naturally raises the question of whether they can also generate dark galactic halos. Of course, the cooling flows observed at the present epoch are mainly confined to the central galaxies in clusters and therefore could not in themselves be responsible for either the cluster dark matter (since this is distributed throughout the cluster) or the halo dark matter in galaxies outside clusters. However, we will argue that one could expect analagous high pressure flows to occur at earlier cosmological epochs and these could have been on much smaller scales than clusters. This conclusion pertains in at least three scenarios for the origin of cosmic structure: the hierarchical clustering scenario, the pancake scenario and the explosion scenario. The implication is that the cooling flows we see today may only represent the endpoint of a process that began at a much earlier phase in the history of the Universe. The details of the different models are given elsewhere (Ashman & Carr 1987). Here we summarize the main results for the hierarchical clustering scenario.

3. COOLING FLOWS IN THE HIERARCHICAL CLUSTERING MODEL

In the "hierarchical clustering" scenario, the first objects to separate out from the Hubble flow and collapse have a scale of about $10^6 M_\odot$, with galaxies and large-scale structure forming through subsequent gravitational clustering. This scenario was originally proposed in the context of a baryon-dominated Universe (Peebles & Dicke 1968) but it is now usually studied in the context of Universes dominated by cold dark matter (Blumenthal *et al.* 1984). In this picture bound regions will lose their identity as they are subsumed within larger bound regions unless they can cool on a dynamical time; for only then will they be able to collapse fast enough to avoid being disrupted by collisions.

If one considers a cloud of mass M which binds at a redshift z, the dynamical time will just be of order the Hubble time at that redshift, whereas the cooling time will depend upon the density and virial temperature of the cloud (which are themselves determined by M and z). Thus one can specify a region in the (M,z) plane in which bound clouds will cool within a dynamical time. This is the region within the shaded line (M_{cool}) in Figure (1). One sees that the cooling condition is satisfied provided the clouds lie within a certain mass range. The lower mass limit is associated with molecular hydrogen cooling and is 10^4-$10^6 M_\odot$; the upper mass limit is associated with hydrogen-helium cooling and is around $10^{11} M_\odot$. [The amount of molecular hydrogen assumed is somewhat model-dependent. If there were none at all, the appropriate lower limit would be given by the broken line; this corresponds to the Lyman-α temperature, below which H/He cooling turns off.] The cooling curve in Figure (1) also has a boundary at z=0, corresponding to the requirement that the clouds bind by the present epoch, and a boundary at $z \approx 10$, corresponding to the Compton cooling of the microwave background.

Now if one considers a cloud well inside the cooling curve in Figure (1), one expects it to fragment immediately, with very little global collapse. In this case, star formation may be efficient but one would anticipate a standard IMF since fragmentation should proceed *isothermally*, as in the Hoyle (1953) hierarchical fragmentation picture. On the other hand, a cloud well outside the cooling curve will not fragment at all. Neither of these situations would be conducive to dark matter production. However, if one considers a cloud which is close to the cooling curve, one can have a situation where the cooling time within the *inner* part of the cloud is less than the Hubble time but greater than the local dynamical time. (This is because, when a cloud virializes, it develops a density profile in which the density decreases with distance from the centre.) This is analagous to the situation with present epoch cooling flows: the fraction of the cloud which can cool in a Hubble time will flow inwards under the pressure of the outer (uncooled) regions and fragmentation will proceed *isobarically* since the sound-crossing time is less than the cooling time. The fraction of the cloud involved will be maximized with a value somewhat less than 1 just outside the cooling curve. This corresponds to what we term a "pervasive pregalactic cooling flow" (PPCF).

In any particular version of the hierarchical clustering scenario, one can specify the mass which is binding as a function of redshift. This corresponds to a line $M_{bind}(z)$ in Figure (1). It is interesting to consider what happens to bound clouds as one follows the $M_{bind}(z)$ trajectory. If the first ones to bind are sufficiently small (as indicated by the dotted part of the line), one expects to start off to the left of the H_2-cooling curve. In this case, the first clouds will be unable to cool and so they will just be obliterated at later stages of the hierarchy. As $M_{bind}(z)$ approaches the cooling curve, one enters the cooling flow regime, with a PPCF occurring as one crosses it. When $M_{bind}(z)$ has penetrated well inside the cooling region, fragmentation becomes efficient but one no longer expects to make dark fragments, since the stars form isothermally rather than isobarically. As $M_{bind}(z)$ crosses the H/He cooling curve, one can have another PPCF phase (at least if enough gas remains) but cooling will cease altogether when M gets sufficiently large. Note that cluster-scale clouds would still be undergoing cooling flows at the present epoch (as observed) but the fraction of mass involved would be small.

The crucial prediction of our model is that, once the form of $M_{bind}(z)$ is specified, there are only two possible epochs at which PPCFs can occur. The associated mass-scales are always of order $10^6 M_\odot$ or $10^{11} M_\odot$ but the redshifts depend on the particular scenario. In the "cold dark matter" picture, for example, the associated redshifts are 30 and 10, respectively. How do we determine which of these alternatives is more plausible? Providing $M_{bind}(z)$ starts off to the left of the H_2-cooling curve, and providing H_2 does in fact form, the smaller scale PPCF is inevitable. In this case, it seems likely that this is the scale at which most of the dark matter will be made since much of the gas will

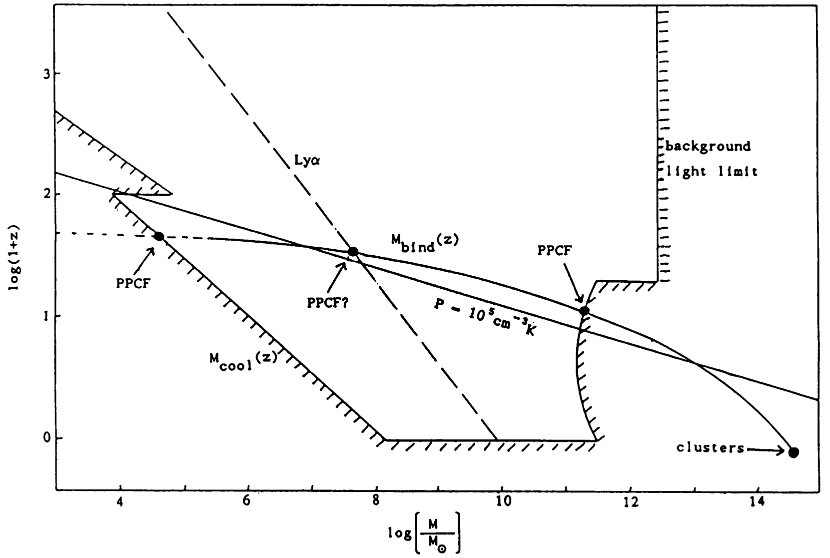

Figure 1. Showing the (M,z) domain in which clouds cool on a Hubble time at high pressure without producing too much background radiation.

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have been consumed by the time $M_{bind}(z)$ crosses the H/He cooling curve. On the other hand, if $M_{bind}(z)$ starts off inside the cooling region, it is possible that isothermal fragmentation will also deplete the gas too much for a PPCF to occur when it reaches the H/He cooling line. In this case, it would be difficult to make dark matter through cooling flows at any stage. Of course, this conclusion would be avoided if H_2-cooling were never important; in this case, the first PPCF phase would occur when $M_{bind}(z)$ crosses the "Lyα" line in Figure (1).

Even if most of the baryons in the Universe are processed through cooling flows, they will only be turned into jupiters if the pressure in the cooling region is large enough. It is not really clear *how* high the pressure has to be, since we cannot claim to have a proper understanding of all the factors which go into determining the fragment mass. Figure (1) shows the line corresponding to $P=10^5 cm^{-3} K$, the sort of pressure associated with cluster cooling flows. If $M_{bind}(z)$ intersects the cooling curve above this line, one at least has empirical reasons for supposing that the PPCFs make jupiters.

An interesting constraint on the scale of PPCFs comes from X-ray background observations. In the hierarchical clustering picture, one can show that the present (redshifted) energy and density of the radiation generated by pregalactic cooling flows depends only on the mass-scale and not the redshift. If the temperature exceeds 0.2 keV, the X-ray background constraints imply that only a small fraction of the halo density can have been processed through cooling flows. This applies for mass-scales larger than about $10^{12} M_\odot$, as indicated by the shaded line on the right of Figure (1), so only galactic or subgalactic scale flows could explain galactic halos.

4. DISCUSSION

Ashman & Carr (1987) discuss the possibility of cooling flows in other cosmological scenarios. In the "pancake" scenario (Zeldovich 1970), the first objects to separate out from the Hubble flow are much larger than galaxies. A currently popular variant of this model arises in the context of a neutrino-dominated universe (Bond *et al.* 1984), when the pancakes have masses $\sim 10^{15} M_\odot$, characteristic of superclusters. In this case, some fraction of the gas in the pancake necessarily undergoes a cooling flow, although the pressure is now imposed by an external shock (rather than an outlying uncooled region) and the fraction of the pancake involved in the cooling flow is rather small (below 20%).

In the "explosion" scenario (Ostriker & Cowie 1981; Ikeuchi 1981), the shocks generated by explosive seeds sweep up vast shells of gas. In a recent version of this theory (Allen & Carr 1987), the shells eventually overlap, so that most of the gas in the Universe is compressed into slabs, very similar to the "pancakes" discussed above. This situation is particularly conducive to cooling flows because the gas is both dense and hot. In both the "pancake" and "explosion" picture, one expects the gas to fragment into clumps, with the clump mass depending on the dominant cooling process: if H/He cooling dominates, one may get galactic-scale clumps, but clumps as small as $10^6 M_\odot$ could arise if H_2 cooling dominates.

It is interesting that, in all three scenarios, the scale on which the dark matter made by cooling flows clumps is either $10^6 M_\odot$ or $10^{11} M_\odot$. This is therefore the scale on which the dark matter should aggregate at the present epoch. If the scale is $10^{11} M_\odot$, cooling flows could make galactic halos directly. If it is $10^6 M_\odot$, the first objects to form would be $10^6 M_\odot$ dark clusters. Galactic halos would then form as a result of the agglomeration of these objects. Possible observational evidence for the second suggestion has been presented by Carr & Lacey (1987), who argue that the $10^6 M_\odot$ objects postulated by Lacey & Ostriker (1985) to explain the observed disk heating are more likely to be dark clusters than massive black holes.

Once galactic halos have formed, it would be fairly natural to generate the dark matter in clusters by tidally stripping the halos from those galaxies within the cluster. Partial support for this view comes from the fact that the mass-to-light ratio of galaxies in cluster cores is less than that for galaxies in the cluster as a whole (Sarazin 1986). On the other hand, it is also possible that some of the cluster dark matter (perhaps most of it) is formed from the non-baryonic background material. Indeed this is obligatory if the cosmological nucleosynthesis upper limit on Ω_b is less than Ω_c.

REFERENCES

Allen, A.J., and Carr, B.J., 1987. Preprint.
Ashman, K.M., and Carr, B.J., 1987. Preprint.
Bond, J.R., Centrella, J., Szalay, A.S., and Wilson, J.R., 1984. *Mon.Not.R.astr.Soc.*, 210, 515.
Blumenthal, G.R., Faber, S.M., Primack, J.R., and Rees, M.J., 1984. *Nature*, 311, 517.
Carr, B.J., and Lacey, C.G., 1987. *Astrophys.J.*, 316, 23.
Carr, B.J., Bond, J.R., and Arnett, W.A., 1984. *Astrophys.J.*, 277, 445.
Faber, S.M., and Gallagher, J.S., 1979. *Ann.Rev.Astron.Astrophys.*, 17, 135.
Fabian, A.C., Nulsen, P.E.J., and Canizares, C.R., 1982. *Mon.Not.R.astr.Soc.*, 201, 933.
Fabian, A.C., Nulsen, P.E.J., and Canizares, C.R., 1984. *Nature*, 310, 733.
Gilmore, G., and Hewitt, P., 1983. *Nature*, 306, 669.
Hegyi, D.J., and Olive, K.A., 1986. *Astrophys.J.*, 303, 56.
Hoyle, F., 1953. *Astrophys.J.*, 118, 513.
Ikeuchi, S., 1981. *Pub.Astron.Soc.Japan*, 33, 211.
Kaiser, N., 1984. *Astrophys.J.Lett.*, 284, L9.
Lacey, C.G., and Ostriker, J.P., 1985. *Astrophys.J.*, 299, 633.
McDowell, J., 1986. *Mon.Not.R.astr.Soc.*, 223, 763.
Ostriker, J.P., and Cowie, L.L., 1981. *Astrophys.J.Lett.*, 243, L127.
Peebles, P.J.E., and Dicke, R.H., 1968. *Astrophys.J.*, 154, 891.
Sarazin, C.L., 1986. *Rev.Mod.Phys.*, 58, 1.
Sarazin, C.L., and O'Connel, R.W., 1983. *Astrophys.J.*, 268, 552.
Silk, J., Djorgovski, S., Wyse, R.F.G., and Gustavo, A.B., 1986. Preprint.
Turner, M.S., and Carr, B.J., 1987. *Mod.Phys.Lett.A.*, 2, 1.
Yang, J., Turner, M.S., Steigmann, G., Schramm, D.N., and Olive, K.A., 1984. *Astrophys.J.*, 281, 493.
Zeldovich, Ya.B., 1970. *Astr.Astrophys.*, 5, 84.