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Star Formation in Cooling Flows*

P. E. J. Nulsen

Department of Physics, University of Wollongong,
P.O. Box 1144, N.S.W. 2500, Australia.

Abstract

There is good evidence that the intracluster gas near the centres of many clusters of galaxies is cooling over at least a decade in temperature. This results in an inflow, which is approximately steady where the cooling time of the gas is shorter than the age of the flow. X-ray observations indicate that the cooling gas must have substantial inhomogeneities. Non-linear development of thermal instability causes cooled gas clouds to be deposited throughout the region of the steady cooling flow. The masses of these clouds will be small, typically a lot less than a Jeans mass when they first form. It is argued that the difficulty of forming large clouds in the bulk of a cooling flow inhibits high mass star formation there. There is evidence of some 'normal' star formation near to the centres of many cooling flows where conditions are more favourable for the formation of giant clouds. The initial mass function is strongly affected by the star formation environment in cooling flows.

1. Introduction

This paper is a selective discussion of cooling flows. A more complete review of cooling flows is given by Fabian *et al.* (1991). Sarazin (1986, 1988) has reviewed the properties of the intracluster gas. Typical central gas densities in clusters of galaxies lie in about the range 10^3–10^4 m^{-3} (e.g. Arnaud 1988), while the gas temperature generally lies in the range 10^7–10^8 K (e.g. Edge and Stewart 1991). Defining the cooling time as the time it would take the gas to radiate its thermal energy at the current rate, we have

$$t_{\mathrm{cool}} = \frac{3p}{2n^2\Lambda(T)} \simeq 7\times 10^{10} T_8^{\frac{1}{2}} n_{-3}^{-1}\,\mathrm{yr}\,, \qquad (1)$$

where p is the gas pressure, Λ is the cooling function, the gas temperature is $T = 10^8 T_8$ K and the electron density is $n = 10^3 n_{-3}$ m^{-3}. This assumes that thermal bremsstrahlung is the principal cause of heat loss, appropriate for gas temperatures in excess of $\sim 3\times 10^7$ K (t_{cool} is shorter than this due to line cooling at lower temperatures).

Based on these numbers, the gas near centres of some clusters ought to cool significantly in a time shorter than the age of the Universe. This has been known

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for some time (Lea *et al.* 1973; Silk 1976), and more recent analysis confirms it. For example, by analysing X-ray images of the clusters of galaxies made with the Einstein Observatory, Arnaud (1988) showed that more than 30% of them have $t_{\rm cool} < H_0^{-1}$ within about 100 kpc of the cluster centre. Here H_0 is the Hubble constant, which we take to be 50 km s^{-1} $\rm Mpc^{-1}$. There is every indication that higher resolution observations would significantly increase this fraction. Given these short cooling times, it would seem likely that some gas has already undergone substantial cooling, and we are observing gas that is cooling now.

The obvious way to look for evidence of cooling is to look for cooled and cooling gas. At X-ray temperatures the best way to do this is by looking for line emission from ionic species that are absent in the hottest intracluster gas. Such lines have been detected in a number clusters (e.g. Canizares *et al.* 1988; Mushotzky and Szymkowiak 1988). For example, Arnaud *et al.* (1991) found the best single temperature fit to the BBXRT spectrum of the Perseus cluster for energies greater than 3 keV is 5·3 keV, and the strength of the 6·7 keV Fe line blend requires an Fe abundance of about 0·57 times cosmic. When they fit this model to the complete BBXRT spectrum, the data show a large excess in low energy emission. The excess is due to emission from ionic species, including some of Fe, which are weak or absent at 5·3 keV. There is clearly a significant, though small, quantity of lower temperature gas present in the cluster.

2. Mass Deposition Rate

In most clusters there is only a small region near the centre where the gas is cooling significantly. The pressure in this region is maintained by the weight of the overlying gas, so that the cooling gas gets compressed as it cools, causing an inflow. This gas flow can be shown to be approximately steady in the region where the cooling time of the gas is shorter than the age of the flow. The bulk of the inflow is highly subsonic, so that inertial effects are minimal and the gas remains nearly hydrostatic (see Section 7).

If we assume that the steady flow is spherically symmetric, then the equation for energy conservation may be put in the form

$$L_X(R) = \dot{M}\,[H(R) + \Delta\phi(R)]\,, \tag{2}$$

where L_X is the total X-ray luminosity from within a sphere of radius R, H is the specific enthalpy of the gas,

$$H = \frac{5kT}{2\mu m_H}, \tag{3}$$

T is the gas temperature and $\Delta\phi(R)$ is the gravitational energy loss (per unit mass) of the gas inside the sphere. The mass flow rate, $\dot{M}$, is the rate of gas flow into the sphere,

$$\dot{M} = 4\pi\rho v R^2, \tag{4}$$

where ρ is the gas density and v its inflow velocity at R. In all known cases the thermal energy input (the term in H) is comparable to or larger than the gravitational term.

Using the X-ray surface brightness profile we can determine $L_X(R)$, so that we can use the energy equation (2) to estimate $\dot{M}$. At the edge of the steady flow, where $t_{\rm cool}(R) \simeq 10^{10}$ yr, the mass flow rate generally lies in the range of a few to a few hundred $M_\odot\,{\rm yr}^{-1}$ (Arnaud 1988). Multiplying this by the likely age of the flows ($\sim 10^{10}$ yr) we find the total mass deposited lies in the range of a few times $(10^{10}$–$10^{12})M_\odot$. At the high end of the range this is equal to the mass of a very large galaxy.

There is an independent method for determining the mass deposition rate in a cooling flow. If the gas cools at constant pressure, then the total power emitted in any line is given by (Nulsen 1988)

$$P_{\rm line} = \frac{5k\dot{M}}{2\mu m_H} \int_0^{T_0} \frac{\Lambda_{\rm line}(T)}{\Lambda(T)}\, dT, \qquad (5)$$

where T_0 is the initial temperature of the gas and $\Lambda_{\rm line}$ is the contribution of the line to the total cooling function. If we pick a low temperature line, then $P_{\rm line}$ depends only on gas abundances and $\dot{M}$, so that this result provides a method for determining $\dot{M}$.

The main weakness of this result is the assumption of constant pressure cooling; however, this is a much better approximation than it first appears. Thermal instability in the cooling flow means that most of the gas cools in the form of small clouds (or blobs) at large radii (see below), so that the late stages of cooling do occur at nearly constant pressure. If we pick a line which is emitted at low temperature relative to T_0, when the cooling is well advanced, the approximation of constant pressure cooling is well justified.

Observations of the line emission by Canizares *et al.* (1979, 1982, 1988) and Mushotzky *et al.* (1981, 1988) give cooling rates that agree well with those obtained from the X-ray surface brightness profile (Fabian *et al.* 1991). This shows that the line emission agrees with the predictions of the cooling models. The lines that have been observed come from gas at temperatures ranging over more than a decade, and they are all consistent with a single cooling rate. The lines come from a variety of elements (Fe, O, S, Ar, Si), but there are also lines from different ionisation species of the same element (particularly Fe).

It has been suggested that perhaps the cooling is a short-lived phenomenon (e.g. Hu 1988). This is difficult to reconcile with the frequent occurrence of cooling flows, but it is even more difficult to reconcile with the agreement between the morphological and spectroscopic determinations for $\dot{M}$. The spectroscopic determinations of the $\dot{M}$ depend, almost exclusively, on the total amount of cooling gas within the field of view of the detector. The morphological determinations depend on our assumption about the lifetime of the cooling flow, since they depend on the total X-ray luminosity from within the region where the cooling time is shorter than the assumed age for the flow. In order for the two determinations to agree we must use the correct age for the cooling flow. While there is some uncertainty in these determinations, we can say that cooling flows must have continued for a substantial fraction of the age of the Universe.

3. Alternative Models

A number of different models have been proposed in order to avoid the deposition of large quantities of cooled gas near to cluster centres. The first requirement for any such model is that it provides an energy input to the cooling flow region which (nearly) balances its X-ray output. The energy input must also have lasted for a substantial fraction of the age of the Universe. The required power is about 10^{36}–10^{38} W, so that the energy source would certainly be significant.

The radiative cooling per unit volume varies with the density as n^2, while the heating per unit volume in many processes is proportional to n. For gas held at constant pressure (a good local approximation in the intracluster medium) there can be no stable equilibrium between heating of this type and radiative cooling (Stewart *et al.* 1984). The cooling is most effective when the temperature is low, while the heating is most effective when it is high. Most local heating mechanisms suffer from this tendency to promote rather than prevent instability. They could prevent cooling, but if so, then we would not expect to see any low temperature gas.

Although it is not a local heating mechanism, thermal conduction suffers from this difficulty (e.g. Nulsen *et al.* 1982; Bregman and David 1988). It is easy to show that the thermal conductive heating is either negligible, or dominant. The observation of the presence of low temperature gas suggests that the thermal conductivity must be suppressed substantially from the magnetic field free value.

Another mechanism that might cause some reduction in mass deposition is heating by supernovae (e.g. Silk *et al.* 1986; Bregman and David 1989). If the cooled gas forms stars with a normal initial mass function, then the resulting supernovae can heat the remaining gas, slowing the rate of gas deposition. In a steady state the significance of this process is measured by considering the mechanical energy yield per unit mass of star formation. This is the energy per unit mass available to heat the next generation of cooling gas. For a standard initial mass function this number is equivalent to about 10^7 K, i.e. enough energy is released per unit mass of star formation to heat the gas turned into stars to about 10^7 K. This is only enough to reduce the cooling rate by a factor of two in the most extreme case. Furthermore, the required supernovae are just not observed.

Finally, it should be noted that no alternative model has even attempted to quantitatively explain the strength of the low temperature emission lines.

4. Distributed Mass Deposition

In a steady, homogeneous cooling flow, the mass flow rate should be independent of the radius. We can determine $\dot{M}$ as a function of the radius using the methods of Section 2. There is some uncertainty in the results (due to uncertainty in the temperature and the gravitational energy loss, $\Delta\phi$), but $\dot{M}$ definitely decreases inward, perhaps as $\dot{M} \propto r$ (Thomas *et al.* 1987; White and Sarazin 1987).

It has long been realised that the cooling gas is prone to thermal instability (Fabian and Nulsen 1977; Mathews and Bregman 1978). The linear development of the thermal instability is weak (Balbus and Soker 1989); however, the thermal instability becomes non-linear when the fractional density excess, $\delta\rho$, satisfies

$$\frac{\delta\rho}{\rho_0} \gtrsim \frac{r}{R}, \tag{6}$$

where ρ_0 is the ambient gas density, R is the distance to the centre of the cluster and r is the 'size' of the perturbed region (usually taken to be spherical for the sake of argument). For small gas 'blobs', this condition is satisfied for small fractional density perturbations. Once a density fluctuation becomes non-linear it will develop further, much faster than a linear perturbation. This can lead to widespread mass deposition, so long as the initial density fluctuations in the gas are appreciable (e.g. Thomas *et al.* 1987), i.e. provided that

$$\left\langle \left(\frac{\delta\rho}{\rho} \right)^2 \right\rangle \sim 1 . \tag{7}$$

The major non-linear effect is the onset of shear and Rayleigh–Taylor instabilities, which disrupt overdense blobs and (effectively) pin them to the mean flow.

The net force (buoyant plus gravitational) on a spherical blob of radius r is

$$\frac{4\pi r^3 \delta\rho G M(R)}{3R^2}, \tag{8}$$

where $M(R)$ is the gravitational mass inside R and $\delta\rho = \rho - \rho_0$ is the excess density in the blob. The free fall time to the centre of the flow is generally much shorter than the flow time (loosely, the inflow is highly subsonic), so that the blob will accelerate quickly if it is not restrained. If it starts moving, the net force on the blob can be balanced by ram pressure,

$$\simeq \pi r^2 \rho_0 v_t^2, \tag{9}$$

where v_t is the terminal velocity of the blob (relative to the mean flow). Alternatively, if the gas is magnetised, the blob may be restrained by magnetic stresses of

$$\lesssim \frac{\pi r^2 B^2}{2\mu_0}, \tag{10}$$

where B is the magnetic field strength.

Inertial stresses disrupt a blob moving at its terminal velocity in about (Nulsen 1986)

$$t_d \simeq \frac{R}{v_{\rm Kepler}} \sqrt{\frac{\rho r}{\delta\rho R}} \simeq \frac{R}{v_{\rm Kepler}} \sqrt{\frac{r}{R}}, \tag{11}$$

when $\rho \gg \rho_0$. Here the Kepler velocity is

$$v_{\rm Kepler}^2 = \frac{GM(R)}{R}. \tag{12}$$

For a small blob, $r \ll R$, the disruption is very fast, and will repeat successively, so that a blob is rapidly shredded into small pieces unless it can be pinned into the ambient flow.

We can estimate the largest blob that could be magnetically pinned in the flow by equating the magnetic stress (10) to the net gravitational force (8). This gives

$$\frac{r_{\max}}{R} \simeq \frac{B^2}{2\mu_0 v_{\mathrm{Kepler}}^2 \delta\rho}, \tag{13}$$

which will generally be small for significant overdensities. Note that this relationship defines a fixed column density of overdense gas. As $\delta\rho$ increases $r_{\max}$ decreases, so that fragmentation will continue as the overdensity amplifies. This means that the unstable cooling blobs will tend to accumulate at around the maximum supportable size. The cooling time also decreases rapidly as the density increases.

This leads to the following general picture. Density fluctuations that are initially non-linear by the criterion (6) get disrupted until they can be pinned into the flow. This will usually have happened before the gas starts cooling significantly. Once blobs are pinned, the growth rate of the thermal instability is appreciable—much greater than for the linearised instability. The timescale for growth is just the cooling time of the gas, which is also the flow time in the region of steady cooling flow, so that the density fluctuations need to be substantial ($\delta\rho/\rho_0 \sim 1$) in order for the gas deposition to be widespread.

As long as the disruption time, t_d, is shorter than the cooling time, overdense gas blobs will continue to be reduced in size as they are amplified. For a blob at the maximum size (equation 13) this condition is violated when

$$t_{\mathrm{cool}} \lesssim t_d, \tag{14}$$

i.e. for

$$T \lesssim 2{\cdot}6 \times 10^6 B_{-6}^{\frac{1}{2}} R_2^{\frac{1}{2}} v_{K,2\cdot5}^{-1} \left(\frac{p}{5{\cdot}7 \times 10^{11}\ \mathrm{K\ m^{-3}}}\right)^{\frac{1}{4}}\ \mathrm{K}, \tag{15}$$

where $B = 10^{-10} B_{-6}$ T, $R = 100 R_2$ kpc and $v_{\mathrm{Kepler}} = 300 v_{K,2\cdot5}$ km s^{-1}. Below this temperature a blob at the maximum size will cool to low temperatures ($T \ll 10^4$ K) without being disrupted again. The maximum mass of a spherical blob when it gets frozen in is

$$M_{\mathrm{freeze}} \simeq 90 B_{-6}^7 R_2^4 v_{K,2,5}^{-8} \left(\frac{p}{5{\cdot}7 \times 10^{11}\ \mathrm{K\,m^{-3}}}\right)^{-\frac{3}{2}} M_{\odot}, \tag{16}$$

which is already small.

Although this mass is very sensitive to its parameters, it should be noted that $r_{\max}$ given by equation (13) is certainly an upper limit to the size of blobs that can be pinned to the flow by the magnetic field. In practice the largest blobs that can be frozen into the flow will be significantly smaller than this. The result is important because it shows that the largest cool blobs deposited by the flow are likely to be very small.

The arguments presented here assume that the inflow is highly subsonic (strictly, $v_{\rm flow} \ll v_{\rm Kepler}$). If this is not true, as is probably the case near to the centre of the flow, the thermal instability is much more effective and the disruption of blobs much less so. We should generally expect much more significant thermal instability and, in particular, the deposition of larger gas blobs, in any region where the Mach number of the flow is appreciable.

5. Origin of the Density Fluctuations

Clusters of galaxies are almost certainly formed by the merger of smaller subclusters. In a merger much of the intracluster gas is probably not shocked, but just mixes to form the new intergalactic medium (e.g. Fabian and Daines 1991). This is particularly true for the lowest entropy gas from the centres of the subclusters. Immediately after a merger this gas will not be at the centre of the new cluster, and must descend through the rest of the gas to get there. In the process there will be extensive mixing of the gas and, if transport processes are inhibited by the presence of a magnetic field, it will result in an inhomogeneous mixture of gases. In short, mergers will produce an inhomogeneous intergalactic medium (see Allen *et al.* 1992 for some limits on this).

At present it is not clear how inhomogeneous the ambient cluster gas needs to be to cause widespread mass deposition in a cooling flow. There can be considerable amplification of the density fluctuations between the time that the gas first starts to cool appreciably and when it gets incorporated into the steady part of the flow. We might reasonably expect the density fluctuations in the ambient gas to be something in excess of 10%, but this is an area requiring further work.

6. Angular Momentum

It is often asked whether angular rotation of the gas is likely to interfere with a steady cooling inflow. It has generally been found that the net rotation in clusters of galaxies is small, so that we should expect the specific angular momentum of the gas to be small too. Despite this, if angular momentum is not transported outward effectively by viscous forces, it can certainly be significant near the centre of the flow. If the rotation velocity of the gas approaches $v_{\rm Kepler}$, then our assumption of spherical symmetry must fail. Of greater significance here, if the cooled and cooling gas is rotationally supported, then the disruption discussed in Section 4 does not occur, and much larger cooled gas clouds could be deposited by the flow.

We need to know the viscosity of the gas. In the absence of magnetic fields this would be roughly

$$\mu \simeq \rho c_s \lambda, \tag{17}$$

where ρ is the gas density, c_s the sound speed in the gas and λ the proton mean free path. It is readily shown that a viscosity of this size would ensure that the angular momentum of the gas was never significant. However, it is likely that the magnetic field which suppresses thermal conduction has a similar effect on the viscosity.

A Reynolds number appropriate for a rotating flow is

$$Re = \frac{1}{\mu}\rho v_\phi R, \tag{18}$$

where v_ϕ is the transverse velocity. If this number is much greater than one, the flow will begin to exhibit shear instability, enhancing momentum transport and hence the effective viscosity. This would push Re back towards unity, to about the point where the shear is marginally unstable. The details are model-dependent, but it is difficult to drive Re to large values. This means that angular momentum is always transported outward faster than it can be convected inward by a cooling flow, provided that the inflow is subsonic.

7. Supersonic Flow

In all known cooling flows the inflow is slow compared to the sound speed in the bulk of the flow. At the outer edge of the steady flow we have

$$v \simeq 6\dot{M}_2^{\frac{1}{3}} t_{10}^{-\frac{1}{3}} T_8^{-\frac{1}{6}} \text{ km s}^{-1}, \tag{19}$$

where $\dot{M} = 100\dot{M}_2\ M_\odot\ \text{yr}^{-1}$, the gas temperature is $10^8 T_8$ K and the cooling time at the edge of the flow is $10^{10} t_{10}$ yr. The flow time, R/v, stays close to the cooling time throughout the steady (subsonic) flow, so that the inflow velocity varies as

$$v \propto \sqrt{\frac{\dot{M}(R)\Lambda(T)}{RT}}, \tag{20}$$

and the Mach number will vary as this divided by $\sqrt{T}$.

Because the dependence of $\dot{M}$ on R is uncertain, it is not clear how the Mach number varies with radius. The general trend of temperature is to decrease inward, at least as the the intracluster gas cools down to the 'virial' temperature of the central galaxy, so that the Mach number probably increases inward. This would mean that there is a central region of supersonic flow.

In a supersonic cooling flow conditions are much more favourable for the deposition of large cooled gas clouds. First, there is insufficient time for clouds to be disrupted by their motion relative to the flow (see Section 4). Second, the transport of angular momentum becomes ineffective, so that the inflow in this region will be become rotationally supported sooner or later (Section 7).

There does seem to be a region in some cooling flows where we see large gas clouds and more-or-less normal star formation. One explanation for this is that these regions occur where the Mach number of the flow becomes significant. In really massive cooling flows like PKS 0745−191 (Fabian *et al.* 1985) the gas may even become rotationally supported so that it stagnates in a disk.

8. Fate of the Cooled Gas

There is a great deal of evidence for cooled gas ($T \ll 10^7$ K) in various forms in cooling flows. Despite this, the amount of cooled gas seen so far probably falls well short of the total amount of cooled gas deposited by a flow. It should be borne in mind that the central galaxies in all cooling flows so far are ellipticals.

There are regions of patchy line emission near the centres of many cooling flows (Hu *et al.* 1985; Johnstone *et al.* 1987; Heckman *et al.* 1989). The gas generally shows low ionisation (e.g. [OII] > [OIII]). The total amounts of line-emitting gas lie in the range of about 10^5–$10^8 M_\odot$. The line luminosity correlates with the cooling rate from a cooling flow but bears no simple relationship to $\dot{M}$. There are some cooling flows that show no line emission at all. The emitting gas shows some systematic and some random motion relative to the accreting galaxy, with velocities of the order of 100 km s^{-1}. It may be rotating in some systems. The line emission is more centrally peaked than the mass deposition (Heckman *et al.* 1989).

Several groups have looked for HI absorption in cooling flows (e.g. Crane *et al.* 1982; Bregman *et al.* 1988; Jaffe *et al.* 1988; McNamara *et al.* 1990). It has been detected in a few cases. In particular, Jaffe (1990) has mapped the HI absorption seen against the radio emission from around NGC 1275 in the Perseus cluster. He detected extended neutral hydrogen near the centre of the galaxy with a total mass of about 10^{10} $M_\odot$. One surprising feature of this observation is that the velocity spread of the gas is about 500 km s^{-1}.

Other groups have also looked for molecular line emission from around cooling flow galaxies (e.g. Lazareff *et al.* 1989; Grabelsky and Ulmer 1990). Mirabel *et al.* (1989) saw CO emission from NGC 1275 requiring a minimum of about 5×10^9 $M_\odot$ of gas (assuming a Galactic CO to H_2 ratio). There are only upper limits for other cases.

The general conclusion we draw from this is that the deposited matter is probably not all stored as detectable gas. This does not quite rule out the possibility that the gas is stored as optically thick molecular clouds. Indeed, White *et al.* (1991) saw excess photoelectric absorption from cooling flows, which could be explained if all of the gas did remain in cold clouds.

9. Normal Star Formation

Normal here means star formation with an initial mass function similar to that in the Galaxy. Most cooling flows show some evidence for the presence of massive young stars. Johnstone *et al.* (1987) and O'Connell and McNamara (1989) found that the spectra of many cooling flow galaxies show an excess of blue emission, indicating the presence of some young stars. Hintzen and Romanishin (1988) found that there is excess blue light from the central regions of these galaxies. The extent of the blue region is similar to that of the 'warm clouds' (the line-emitting clouds and HI clouds of the previous section), perhaps 5 kpc.

The amount of excess blue light correlates with the mass deposition rate of the cooling flow, but again there is no simple relationship between the two. The blue light can be modelled as being due to a small amount of star formation. The UV spectrum of the central galaxy in A2597 requires an upper mass cutoff at about 1·5–2 $M_\odot$ (Crawford *et al.* 1989). Earlier stars have been seen in other systems: A stars in NGC 1275 (Rubin *et al.* 1977); OB stars in NGC 1275 (Shields and Filippenko 1990). The presence of dust has made modelling difficult due to the uncertainty of the reddening corrections. The total amount of star formation of this type is generally small. Even allowing for the distributed mass deposition, only about 10% of the cooled gas can be turning into stars with a Galactic initial mass function.

It is interesting to find that there is some continuing star formation in cooling flows. As mentioned in Section 7, this may be associated with a region of supersonic flow, where relatively large cool clouds can be deposited.

10. Low Mass Star Formation

Assuming that all of the cooled gas forms into stars, simple arguments based on colours and total luminosity show that the mean mass of the resulting stars must be less than about 1 $M_\odot$ (Fabian *et al.* 1982). Arnaud and Gilmore (1987) showed that the 2·3 μm CO feature is similar in cooling flow and non-cooling flow galaxies. This puts some constraint on the ratio of red giants to low mass dwarfs, so that we cannot allow models in which the 2·3 μm luminosity is dominated by low mass dwarfs. At present it is not clear what quantitative constraint this puts on the initial mass function.

Johnstone and Fabian (1992) assumed that the star formation rate would roughly follow the mass deposition rate, so they considered models in which the new stars are distributed with $\rho_* \propto R^{-2}$. They tested a range of power law initial mass functions for the halo of the central galaxy in A2199. They found that they needed an upper mass cutoff of $\lesssim 1\, M_\odot$ to be consistent with the observed surface brightness profile for this galaxy. The same constraint for M87 is much more severe.

Although the data are still patchy, we can definitely say that the bulk of the cooled gas must form very low mass objects—if it does collapse gravitationally.

11. Discussion and Conclusions

X-ray imaging and spectroscopic data provide good evidence that hot gas near the centres of some clusters is cooling over at least a decade in temperature. It is difficult to see how the gas could cool so far without ending up cooling to well below 10^4 K. X-ray imaging (and to some extent spectroscopic) data also show that the cooling gas must have appreciable inhomogeneities which cause cooled gas to be deposited throughout the steady cooling flow—out to about 100 kpc in the larger flows. This requires that the thermal conductivity of the gas be significantly suppressed from its magnetic field free value. The non-linear development of thermal instability causes the cooled gas to be deposited as a spray of low mass clouds. In simple terms, this happens because the cooled gas has to be supported by the other gas and magnetic fields, a situation which is basically unstable. This does not apply in any region where the Mach number of the flow becomes appreciable, or if the flow is rotationally supported rather than pressure supported.

From a theoretical point of view, it is difficult to see how the small cooled clouds can aggregate into large clumps. The Jeans mass is very low in the cooled gas, perhaps less than 0·1 $M_\odot$ based on recent calculations by Ferland *et al.* (1992), since the conditions of the cooling flow allow the gas to cool to very low temperatures. Perhaps the cooled gas in the bulk of the flow really can end up collapsing into very small bound objects.

There are larger cool clouds near the centres of many cooling flows. Apart from the greater propensity for large clouds to form where the Mach number of the flow is larger, there will be a larger density of cooled clouds in this region. Indeed, the total amount of cool gas observed in this region may exceed the amount of hot gas in the region. Under these conditions cloud coalescence can also enhance the formation of large clouds. It is the larger clouds of cool gas that probably give rise to the more massive stars seen in many cooling flows.

The argument proposed here is that cooling flows form mainly low mass stars, ultimately, because the gas in the bulk of the flow is pressure supported, rather than being rotationally supported or in near free fall. This clearly has implications for the history of galaxy formation generally (e.g. Thomas and Fabian 1990). If these arguments are correct, then nearly all luminous matter in the Universe must have been formed in kinematically cold (sub)systems. Perhaps spherical collapse leads exclusively to dark matter, and elliptical galaxies have to be formed by mergers of disk galaxies.

References

Allen, S. W., Fabian, A. C., Johnstone, R. M., Nulsen, P. E. J., and Edge, A. C. (1992). *Mon. Not. R. Astron. Soc.* **254**, 51.

Arnaud, K. A. (1988). *In* 'Cooling Flows in Clusters and Galaxies' (Ed. A. C. Fabian), p. 31 (Kluwer: Dordrecht).

Arnaud, K. A., and Gilmore, G. (1987). *In* 'Structure and Dynamics of Elliptical Galaxies' (Ed. T. de Zeeuw), p. 445 (Reidel: Dordrecht).

Arnaud, K. A., Serlemitsos, P. J., Marshall, F. E., Petre, R., Jahoda, K., Boldt, E., Holt, S. S., Mushotzky, R. F., Swank, J. H., and Szymkowiak, A. E. (1991). NASA preprint of Contributions to the 28th Yamada Conference on Frontiers of X-ray Astronomy, Nagoya, p. 28.

Balbus, S., and Soker, N. (1989). *Astrophys. J.* **341**, 611.

Bregman, J. N., and David, L. P. (1988). *Astrophys. J.* **326**, 639.

Bregman, J. N., and David, L. P., (1989). *Astrophys. J.* **341**, 49.

Bregman, J. N., Roberts, M. S., and Giovanelli, R. (1988). *Astrophys. J. Lett.* **330**, 93.

Canizares, C. R., Clarke, G. W., Markert, T. H., Berg, C., Smedira, M., Bardas, D., Schnopper, H., and Kalata, K. (1979). *Astrophys. J. Lett.*, **234**, 33.

Canizares, C. R., Clarke, G. W., Jernigan, J. G., and Markert, T. H. (1982). *Astrophys. J.* **262**, 33.

Canizares, C. R., Markert, T. H., and Donahue, M. E. (1988). *In* 'Cooling Flows in Clusters and Galaxies' (Ed. A. C. Fabian), p. 63 (Kluwer: Dordrecht).

Crane, P., van der Hulst, J., and Haschick, A. (1982). Proc. IAU Symp. No. 97, Extragalactic Radio Sources (Eds D. S. Heeschen and C. M. Wade), p. 307 (Reidel: Dordrecht).

Crawford, C. S., Arnaud, K. A., Fabian, A. C., and Johnstone, R. M. (1989). *Mon. Not. R. Astron. Soc.* **236**, 277.

Edge, A. C., and Stewart, G. C. (1991). *Mon. Not. R. Astron. Soc.* **252**, 414.

Fabian, A. C., and Daines, S. J. (1991). *In* 'Clusters and Superclusters of Galaxies, Contributed Talks and Poster Papers' (Eds M. M. Colless *et al.*), p. 111 (Inst. of Astronomy: Cambridge).

Fabian, A. C., and Nulsen, P. E. J. (1977). *Mon. Not. R. Astron. Soc.* **180**, 479.

Fabian, A. C., Nulsen, P. E. J., and Canizares, C. R. (1982). *Mon. Not. R. Astron. Soc.* **201**, 933,

Fabian, A. C., Arnaud, K. A., Nulsen, P. E. J., Watson, M. G., Stewart, G. C., McHardy, I., Smith, A., Elvis, M., and Mushotzky, R. F. (1985). *Mon. Not. R. Astron. Soc.* **216**, 923.

Fabian, A. C., Nulsen, P. E. J., and Canizares, C. R. (1991). *Astron. Astrophys. Rev.* **2**, 191.

Ferland, G., Fabian, A. C., and Johnstone, R. M. (19992). In preparation.

Grabelsky, D., and Ulmer, M. P. (1990). *In* 'The Interstellar Medium in External Galaxies; Summary of Contributed Papers' (Eds D. J. Hollenbach and H. A. Thronson), p. 206 (NASA Conference Publication 3084).

Heckman, T. M., Baum, S. A., van Breugel, W. J. M., and McCarthy, P. (1989). *Astrophys. J.* **338**, 48.
Hintzen, P., and Romanishin, W. (1988). *Astrophys. J. Lett.* **327**, 17.
Hu E. M. (1988). *In* 'Cooling Flows in Clusters and Galaxies' (Ed. A. C. Fabian), p. 73 (Kluwer: Dordrecht).
Hu, E. M., Cowie, L. L., and Wang, Z. (1985). *Astrophys. J. Suppl.* **59**, 447.
Jaffe, W. (1990). *Astron. Astrophys.* **240**, 254.
Jaffe, W., de Bruyn, A. G., and Sijbreng, D. (1988). *In* 'Cooling Flows in Clusters and Galaxies' (Ed. A. C. Fabian), p. 145 (Kluwer: Dordrecht).
Johnstone, R. M., and Fabian, A. C. (1992). In preparation.
Johnstone, R. M., Fabian, A. C., and Nulsen, P. E. J. (1987). *Mon. Not. R. Astron. Soc.* **224**, 75.
Lazareff, B., Castets, A., Kim, D.-W., and Jura, M. (1989). *Astrophys. J. Lett.* **336**, 13.
Lea, S. M., Silk, J., Kellogg, E., and Murray, S. (1973). *Astrophys. J. Lett.* **184**, 105.
McNamara, B. R., Bregman, J. N., and O'Connell, R. W. (1990). *Astrophys. J.* **360**, 20.
Mathews, W. G., and Bregman, J. N. (1978). *Astrophys. J.* **244**, 308.
Mirabel, I. F., Sanders, D. B., and Kazes, I. (1989). *Astrophys. J. Lett.* **340**, 9.
Mushotzky, R. F., Holt, S. S., Smith, B. W., Boldt, E. A., and Serlemitsos, P. J. (1981). *Astrophys. J. Lett.* **244**, 47.
Mushotzky, R. F., and Szymkowiak, A. E. (1988). *In* 'Cooling Flows in Clusters and Galaxies' (Ed. A. C. Fabian), p. 53 (Kluwer: Dordrecht).
Nulsen, P. E. J. (1986). *Mon. Not. R. Astron. Soc.* **221**, 377.
Nulsen, P. E. J. (1988). *In* 'Cooling Flows in Clusters and Galaxies' (Ed. A. C. Fabian), p. 175 (Kluwer: Dordrecht).
Nulsen, P. E. J., Stewart, G. C., Fabian, A. C., Mushotzky, R. F., Holt, S. S., Ku, W. H. M., and Malin, D. F. (1982). *Mon. Not. R. Astron. Soc.* **199**, 1089.
O'Connell, R. W., and McNamara, B. R. (1989). *Astron. J.* **98**, 180.
Rubin, V. C., Ford, W. K., Petterson, C. J., and Oort, J. H. (1977). *Astrophys. J.* **211**, 693.
Sarazin, C. L. (1986). *Rev. Mod. Phys.* **58**, 1.
Sarazin, C. L. (1988). 'X-ray Emission from Clusters of Galaxies' (Cambridge University Press).
Shields, J., and Filippenko, A. (1990). *Astrophys. J. Lett.* **253**, 7.
Silk, J. (1976). *Astrophys. J.* **208**, 646.
Silk, J., Djorgovski, G., Wyse, R. F. G., and Bruzual, G. A. (1986). *Astrophys. J.* **307**, 415.
Stewart, G. C., Canizares, C. R., Fabian, A. C., and Nulsen, P. E. J. (1984). *Astrophys. J.* **278**, 536.
Thomas, P. A., and Fabian, A. C. (1990). *Mon. Not. R. Astron. Soc.* **246**, 156.
Thomas, P. A., Fabian, A. C., and Nulsen, P. E. J. (1987). *Mon. Not. R. Astron. Soc.* **228**, 973.
White, D. A., Fabian, A. C., Johnstone, R. M., Mushotzky, R. F., and Arnaud, K. A. (1991). *Mon. Not. R. Astron. Soc.* **252**, 72.
White, R. E., and Sarazin, C. L. (1987). *Astrophys. J.* **318**, 621.

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