HOT GAS IN CLUSTERS OF GALAXIES

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I. INTRODUCTION AND OBSERVATIONAL DATA

The idea that gas may be present in clusters of galaxies originated with the missing mass problem--the observation that galaxies in clusters were moving so fast that the inferred galaxy masses (using conventional mass to light ratios for the galaxies) were not enough to hold them together caused astronomers to speculate that the "missing mass" was in the form of gas. Subsequent observations in the 21 cm and Lα lines as well as radio, optical and x-ray continuum observations have effectively ruled out this possibility in a large number of clusters. However, there is evidence for the presence of gas in smaller quantities in many clusters.

If gas is present in clusters, and is spread uniformly throughout the cluster, then it must be hot. The gas is subject to the same gravitational field as the galaxies, and therefore particle velocities of the order of the velocity dispersion in the cluster are necessary if the gas is not to collapse to the center of the cluster. Cooler gas may be present in the form of clouds which support themselves by their orbital motion, although there is no strong evidence for their existence as a general rule in clusters.

The primary observational evidence for the existence of hot gas is the x-ray and radio data which are summarized in this volume. Ignoring such exotic mechanisms as clouds of accreting black holes, there are two main possibilities for the origin of the x-ray emission. These are that the x-rays are thermal bremsstrahlung from a hot gas, or that they are the result of inverse compton scattering of high energy electrons off the 3K background. High energy electrons must be present in clusters such as Coma and Perseus which have radio halos. However, if the magnetic field is sufficiently weak that the ratio of inverse compton to synchrotron emission is of the right order, then the electrons which give rise to observed radio emission via the synchrotron process will contribute inverse compton radiation at energies much greater than the observed x-ray emission. Similarly, electrons giving rise to the

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observed x-ray photons have their synchrotron emission at frequencies well below the observed radio halo emission. Therefore, the observation of a radio halo is not direct evidence for the inverse compton model, (e.g. Cavaliere and Fusco-Femiano, 1976; Harris and Romanishin, 1974). The x-ray spectrum is most important in discriminating between the two models. Recent data from Uhuru, (Kellogg et al., 1975), OSO 7 (Ulmer et al., 1973) and Ariel V (Mitchell et al., 1976), balloon data (Scheepmaker et al., 1976) and rocket data (Malina et al., 1976) fit an optically thin bremsstrahlung spectrum but do not fit a single power law model, although more complex non-thermal models are possible. The temperature indicated by these spectra is $\sim 10^8$K, in the range one would expect for hot gas in these clusters.

Radio "tails," such as 3C129, are most easily explained as the interaction between a fast moving radio galaxy and a surrounding medium. Both ram pressure due to the galaxy's motion and thermal pressure of the external medium are important in determining the galaxy structure (e.g. Jaffe and Perola, 1973; Cowie and McKee, 1975; Pacholczyk and Scott, 1976). The predominance of steep spectrum radio sources in clusters (Baldwin and Scott, 1973; Colla et al., 1975a) is further evidence for the presence of gas. Such sources can be explained if the radiating plasma is confined by an external medium, the lifetime then increases and the spectrum steepens by synchrotron losses. The galaxies themselves often show effects of interaction with an intergalactic gas. This is discussed further in §III below.

The evidence is further strengthened by the correlations between the various different observations. All radio tail sources observed to date (in this category I include the wide angle tail or "V" sources) occur in clusters. All of these clusters of distance class <4 (Abell 1958), with the exception of one of richness class 0 and two Zwicky clusters, also have x-ray emission. (See Tables I and II.) Thus, where there is one indicator of gas, there are often two. The more distant clusters may also be x-ray sources, beyond the limit of present detectors. In what follows, I shall assume that the x-rays are produced by thermal bremsstrahlung.

It is possible to calculate the density and temperature of the intracluster gas (hereafter ICG) from the x-ray data and radio data independently. The x-ray spectrum, interpreted as thermal bremsstrahlung from an isothermal gas, indicates a temperature of $\sim 10^8$K. The density can then be calculated from the source intensity and distance, and the temperature as determined from the spectrum, and is typically a few x 10^{-3} cm^{-3}. Both these quantities are expected to decrease as the distance from the cluster center increases. Theories of the radio tails generally require that ram pressure confine the head of the source, and thermal pressure confine the tail. Thus, with some knowledge of the galaxy velocity, the density and temperature of the confining medium can be calculated. These values are typically a density of at least a few 10^{-4} cm^{-3}, and a temperature of a few 10^7 K. These values are consistent with the x-ray data, and the fact that the radio

TABLE I
CLUSTERS HAVING RADIO TAILS AND X-RAY EMISSION

Cluster	Dist.	Rich.	X-ray (3U)	Radio	Ref.	Type	Dir.	Red-shift	Ref.
A347	1	0	0227+43	3C66	MV,No	V	In	.02	M^4
A401	3	2	0254+13	4C13.17A	RO,S	Tail	Out	.08	RO
A426	0	2	0316+41	3C83.1B	M,Ri	Tail	Out	.02	CR
				3C83.2	WMV				
				0314+413	MPVV	Tail	In		
A1367	1	2	1144+19	3C624	F	Tail	In	.02	N
A1656	1	2	1257+28	5C4.81	RO,JP	Tail	Out	.02	RPKK
A2151	1	2	1551+15	4C17.66	JP	Tail?	In	.03	N
A2199	1	2	1639+40	3C338	JP	V	In	.03	N
A2241†	3	0	1706+32	4C32.52E	R	Tail	Out	.1	SB
A2255	3	2	*	4CT64.201A	RO,S	Tail	In	.07	Z
A2256	3	2	1706+78	1706+786	RO	Tail	††	.06	U
A2634	1	1	2346+26	3C465	MV	V	Out	.03	N
3C129Cluster		-	0446+44	3C129	M,Ri	Tail	‡	.02	Sp

Notes: *Ariel V source, Cooke and Maccagni, 1976. †Five 4C sources in 2 superposed clusters. ††Projected tail direction is tangential. ‡Cluster center unknown.

References: CR Chincarini and Rood, 1971. F Fomalont, 1971. JP Jaffe and Perola, 1974. M Miley, 1973. M^4 Minkowski, in Maltby, Mathews and Moffet, 1963. MV Miley and van der Laan, 1973. N Noonan, 1973. No Northover, 1973. R Riley, 1975. Ri Riley, 1973. RPKK Rood et al., 1972. RO Rudnick and Owen, 1976. S Slingo, 1974. Sp Spinrad, 1975. SB Spinrad and Bahcall, 1976. U Ulrich, 1976. WMV Wellington et al., 1973. Z Zwicky, 1971.

tails to which these models have been applied are generally not found at the center of the clusters. The x-ray intensity and spectrum constrain the gas parameters fairly well, and the results are not very model dependent. However, the values inferred from the radio tails are somewhat more model dependent. These numbers indicate that the total mass of gas in the cluster is of the order of that present in the galaxies (ignoring the possibility that the galaxies have massive halos) and fails by a wide margin to bind the cluster.

II. THEORY: ORIGIN AND DYNAMICS OF THE GAS

If the gas is present in clusters, it is natural to ask whence it came. It may be primordial, a remnant of the cluster formation process, or it may have been shed from the galaxies, or some combination of the two. The rather large total mass present indicates that an origin entirely in the galaxies is perhaps unlikely.

Primordial gas has been considered by Gunn and Gott (1972), Lea (1976) and Takahara et al. (1976). The cluster of galaxies forms a potential well into which intercluster matter, if it exists, will fall.

TABLE II
CLUSTERS WHICH HAVE TAILS BUT NO X-RAY EMISSION

Cluster	Dist. Class	Rich. Class	Red-shift	Ref.	Source	Type	Ref.
A84	5	1	.12	RO	4C21.05	Tail	R,RO
A629	5	1	.14	RO	0810+665	Tail	RO
A1190	5	2	.07	U	4C41.23	Tail	OR*
A1314	1	0	.03	N	IC711	Tail	VW
					IC708	V	OR
A1446	5	2	.13	OR	1159+583	V?	OR
A1452	4	0	.06	U	1200+519	Tail	RO
A1559	5	1	.15	OR	1231+674	V?	OR
A1940	5	3	.13	OR	1433+553	V?	OR
A2214	6	0	.18	OR	1636+379	V?	OR
A2220	6	0	.11	U	4C53.37	V?	OR*
A2250	5	1	.06	U	1709+397	Tail	RO
A2304	5	0	.13	OR	1819+689	V	OR
ZW2247+1107	-	-	.03	U	PK2247+11	Tail	F,SE
ZW1615+3025			.03	C	NGC6109	Tail?	C
					NGC6137	Tail?	C

References: C Colla et al., 1975b. F Fomalont, 1971. N. Noonan, 1973. OR Owen and Rudnick, 1976. OR* Owen and Rudnick, unpublished. R Riley, 1975. RO Rudnick and Owen, 1976. SE Schilizzi and Ekers, 1976. U Ulrich, 1976. VW Valle and Wilson, 1976.

As it falls into the cluster it heats to a temperature which is determined by the cluster mass and concentration, generally $\sim 10^8$ -10^9K. This gas then emits x-rays by thermal bremsstrahlung. In the absence of any dissipation, the gas will re-expand out of the cluster. However, if the gas can lose its excess energy it will collect in the cluster center. The primary form of energy loss is thermal bremsstrahlung cooling, which becomes important as the density of the infalling gas increases. Using standard Friedmann models for the universe, and assuming that the infall begins at $z = 4$, cooling becomes important for values of $\Omega (= 8\pi G\rho/3H_o^2$, where H_o is the Hubble constant) $\gtrsim .2$ for $H_o = 50$ km s^{-1} Mpc^{-1}. If the redshift of cluster collapse is less than 4, then $\Omega_{crit} > .2$, and vice versa. Heat should also be conducted outward from the cluster center by thermal conductivity at values of Ω up to 1, causing the gas to collapse to the center. However, magnetic fields must be present in many clusters since large halos of synchrotron radio emission are observed (e.g. Ryle and Windram, 1968; Jaffe et al., 1976) and this field may be effective in suppressing the thermal conductivity. Conductivity will be neglected in what follows. If $\Omega < .2$, the gas bounces after the initial collapse and oscillates about an equilibrium position. The amplitude and timescale of the oscillations depend on the viscosity, and differ in the calculations quoted above, presumably because of differences in numerical viscosity. While molecular viscosity is expected to be very small, turbulent or magnetic viscosity may be quite important in the ICG. When the oscillations damp out, the gas distribution approaches the static distribution discussed below.

If gas is flowing into the cluster, then the radio tails should point towards toward the cluster center. In fact, as many tails point inwards as outwards, (see Table II), indicating that any inflow velocity is dominated by the galaxy motion, and bulk motion of the ICG is not important in determining the radio structure.

Gas outflow from the cluster has been postulated by Yahil and Ostriker (1973). These authors claimed that gas shed from the galaxies would feed an outflowing wind. The wind velocity in this model is probably not high enough to affect the radio tail structure. However, a rather large amount of energy is required to power the wind. The heating mechanisms considered were heating from within the galaxies, e.g. by supernovae, or heating by friction; that is, heating by the shocks which form when a galaxy moves supersonically through the surrounding medium. If heating occurs in the galaxies, a supernova rate of ∿1700 $h^{-3/2}$ yr (h is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}) is required in the cluster, whereas ∿3 are observed. Heating by friction is inefficient in the transonic regime (Lea and De Young, 1976) so that temperatures in excess of a few 10^7 K cannot be attained by this mechanism. In addition, the existence of an intercluster medium, even if its density is low ($\Omega<.2$), may be sufficient to inhibit the wind. Explosive events may blow gas out of the clusters prior to the onset of the wind (Schwartz et al., 1975) but this leads to the bizarre situation of all the gas being kept between the clusters by the wind.

A third model in which the gas is in static equilibrium in the gravitational field of the cluster has been described by Lea (1975), Gull and Northover (1975), Cavaliere and Fusco-Femiano (1976) and Shibazaki et al., (1976). A model of this type is approached by infall models with $\Omega \lesssim .2$ at large times, and this may be the most satisfactory model. It seems to provide the best fit to the data in terms of its spatial distribution and spectrum, at least for the "simple" clusters, like Coma, which seem to be gravitationally relaxed and have a single x-ray emitting region. If the gravitational potential of the cluster is $\phi(r)$, and the gas in the cluster extends to a distance r_o, where it is in pressure equilibrium with an external medium whose pressure p_o is much less than the pressure in the center of the cluster, then the temperature and density are given by

$$T(r) = \phi(r)\mu(\gamma-1)/(\gamma k)+T_\infty \qquad (1)$$

and

$$n(r) = n_c[T(r)/T_c]^{1/(\gamma-1)} \qquad (2)$$

where μ is the mean molecular weight, k = Boltzmann's constant. The central temperature T_c is

$$T_c = \phi(o)\mu(\gamma-1)/(\gamma k)+T_\infty = T_o + T_\infty \qquad (3)$$

and

$$T_\infty = -\phi(r_o)\mu(\gamma-1)/(\gamma k) \qquad (4)$$

Using the cluster model described by King (1972) and writing $y = r/a$ where a is the core radius, equation (1) becomes

$$T(r) = T_o \left\langle \{\ell n[y+(1+y^2)^{1/2}]\}/y - \{\ln[y_o+(1+y_o^2)^{1/2}]\}/y_o \right\rangle \quad (5)$$

$$T_o = 3GM_c\mu(\gamma-1)/(\gamma a) \quad (6)$$

Here M_c is the cluster core mass. These models are characterized by a density distribution which is more extended than the galaxy distribution (for $\gamma>1$) and a temperature which is almost isothermal in the core, but decreases for $y > 1$. The distribution becomes more compact, and T_c decreases, if either r_o or γ decreases (see Figure 1). Decreasing r_o also steepens the temperature curve, while decreasing γ does not (see Figure 2). Values of $y_o \lesssim 10$ are not acceptable, ($T_\infty \lesssim -.3T_o$), since the cluster gravity is still appreciable, and central densities are high enough that cooling may be important (Gull and Northover, 1976).

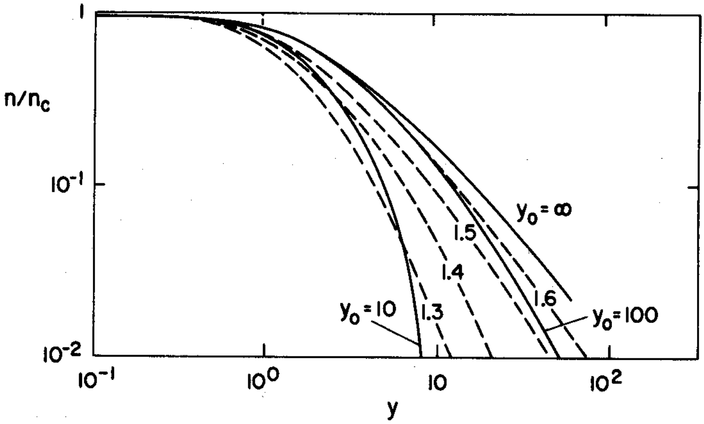

Fig. 1: Density profiles in the adiabatic model. Solid lines, $\gamma = 5/3$. Dashed lines labelled with values of γ have $y_o = \infty$.

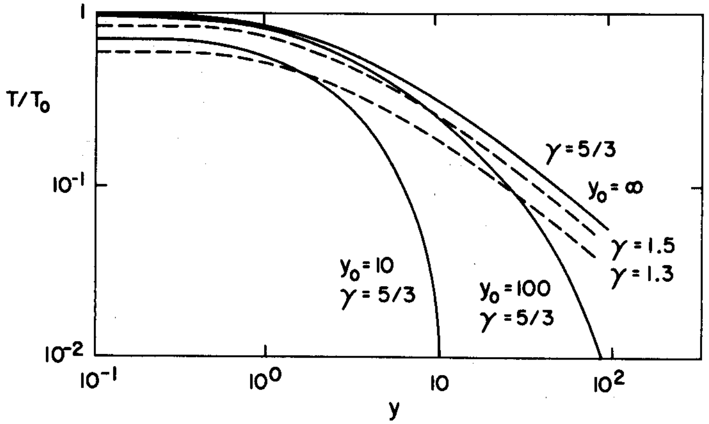

Fig. 2: Temperature in units of T_o for the adiabatic model. Curves are labelled with y_o and γ, except dashed lines have $y_o = \infty$ and γ as shown.

Since the cluster can be easily identified out to $y \sim 40$ (Rood et al., 1972), values of $y_o \gtrsim 40$ are perhaps preferable. Value of $\gamma < 5/3$ are also allowable, since the presence of relativistic gas (electrons powering the radio halo) and thermal conduction both reduce the value of γ. Although these models can be distinguished by the x-ray data, particularly space resolved spectroscopy, current detectors do not have the sensitivity for this.

The adiabatic models have density profiles which drop off fairly slowly in the outer regions, and this may be important for the existence of radio tails. For example, if $y_o = \infty$, $\gamma = 5/3$, the density is high enough to affect radio source structure out to 20 core radii from the cluster center. These cluster "halos" may also have important implications for the x-ray background.

It is interesting to consider the x-ray luminosity-velocity dispersion relationship first discussed by Solinger and Tucker (1972) in the light of the models discussed above. A recent compilation of the data is given in Figure 3, although it should be borne in mind that not all of the x-ray identifications are secure and some of the clusters may actually be two clusters (e.g. 2241, 2139, 2255). According to Faber and Dressler (1976) a correlation of L_x with Δv exists at the 2.2σ level. Certainly, all the clusters observed to be x-ray sources (except A262) have $\Delta v > 1000$ km s^{-1}. From equation (6) and the work of Rood et al. (1972),

$$T_o = 3(\Delta v)^2 \mu(\gamma-1)/(\gamma k) \qquad (7)$$

For $\Delta v = 1000$ km s^{-1}, $T_o \sim 8 \times 10^7$ K. Clusters having $\Delta v < 1000$ km s^{-1} should thus be expected to produce x-rays only at energies $\lesssim 7$ keV, and thus luminosities in the 2 - 10 keV band should decrease as Δv decreases below 1000 km s^{-1} regardless of the amount of gas present. Perhaps this is all the L_x-Δv plot has to tell us. X-ray spectra will determine whether equation (7) is valid. A relation similar to this is predicted by all three classes of models (inflow, outflow, and static) but only the static model allows a mass of gas independent of the cluster mass. More elaborate models have been constructed for the L_x - Δv relationship (e.g. Silk, 1976) but the data does not seem to warrant their use at the present time.

Finally, I should like to comment on the discovery of an iron line in the spectrum of Perseus cluster of galaxies (Mitchell et al., 1976). This is strong evidence that we are seeing thermal emission from a hot gas. The iron line is due to several transitions in FeXXV and FeXXVI which peak at a temperature of $T \sim 5 \times 10^7$ K. The (isothermal) temperature for this cluster determined independently by Kellogg et al. (1975) and Malina et al., (1976) is 7.9×10^7 K. This temperature also fits the spectrum at higher energies (Scheepmaker et al., 1976). At this temperature, the iron line as observed will be produced with an iron abundance (in the inner 1-2 core radii of the cluster) of $\sim .2$ the solar abundance. One would expect approximately one fifth of the total gas needed to produce the x-rays to be shed

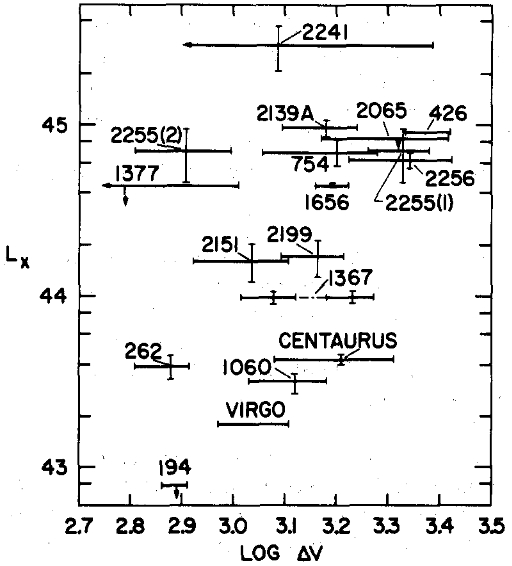

Fig. 3: L_x versus velocity dispersion. Data from Faber & Dressler (1976) except: 2255 from Cooke & Maccagni (1976); 2255 (1) and (2) show velocity dispersion on the basis that 2255 is one or two clusters (Tarenghi and Scott 1976); 2199, L_x from Cooke & Maccagni 1976; 1060, L_x from Ives and Sanford 1976; 2241, values derived from data in Spinrad and Bahcall 1976.

into the cluster by the galaxies themselves over ∿ 10^{10} years (Mathews and Baker, 1971; Larson and Dinerstein, 1975; Lea and De Young, 1976), and again this illustrates that the static model is perhaps most reasonable.

On the other hand, taking solar abundance as an upper limit to the abundance of iron in the cluster, one obtains an upper limit to the temperature of the gas of 2 x 10^8 K, which is less than the temperature T_o (= 4.7 x 10^8 K) predicted by equation (7) with $\gamma = 5/3$. The lower temperature implied by the spectrum obtains for $\gamma \sim 1.07$ or $\gamma_o \sim 1.3$. These values seem rather improbable and perhaps indicate that this cluster is not dynamically relaxed. In view of the spatial complexity of this source, the spectrum may also be complex, and the thermal explanation may be an oversimplication.

Should a similar line be observed in the Coma cluster? This cluster has a higher observed temperature (references above) of 10^8 K. At this temperature, the line is ∿.67 the intensity as compared with $T \sim 7 \times 10^7$ K, also the line to continuum ratio in a 6--7 keV bandpass is down by a factor of 3, for the same iron abundance. The line would therefore be present at ∿ 2σ if the source in Coma were as strong as Perseus. Since the source is weaker by a factor ∿3, lack of observation of a line in Coma is quite consistent with the presence of iron in Coma as in Perseus. For Coma, $T_o \sim 1.9\ 10^8$. $T_c \sim 10^8$ is obtained for $\gamma = 1.27$ or $y_o \sim 5$. When adiabatic models are fit to the data, generally T_c is slightly greater than the isothermal temperature, allowing larger values of γ and y_o, (e.g. Lea 1975, Mitchell et al., 1976).

III. EFFECTS OF THE GAS

Since the galaxies have observed velocities of up to 2000 km s^{-1} in rich clusters, they will experience an appreciable ram pressure due to the surrounding gas. This pressure is expected to have noticeable effects on the galaxies, the most spectacular of which is the formation of the radio tail galaxies, discussed above. Other effects which have been suggested are the stripping of interstellar gas from the galaxies, and heating of the ICG by the galaxies. Stripping has been considered by Gunn and Gott (1972), Tarter (1975), Lea and De Young (1976) and Gisler (1976). These authors find that gas is stripped for galaxy velocities greater than Mach 1, even in the transonic regime (Mach numbers $\sim$1). The rate of stripping increases with the galaxy velocity. Slow moving galaxies such as may be present in the central regions will retain their gas and may even accrete gas shed from the other galaxies. Once this shed gas has heated to the temperature of the ICG, which it will do by collisions and conductivity, accretion is unlikely. Fast moving galaxies will lose most of their gas in a few 10^9 years, leaving the remainder in a hot, unobservable state. This may have important implications for the formation of radio sources, if galactic gas which has collapsed to the galactic center is necessary for this. Indeed, radio sources do tend to occur more frequently in the central (probably slow-moving) galaxies, (McHardy 1974, Guthrie 1974, Tovmassian and Shirbakyan 1974). There is also evidence for gas poor galaxies in clusters, for example, the anaemic spirals discussed by Van den Bergh (1976), and the possibility of hydrogen poor spirals in the Virgo cluster (Davies and Lewis 1973, but see also Bottinelli and Gouguenheim 1974). Also, the traditionally gas poor galaxies (ellipticals and some SO's) occur more often in rich, centrally condensed clusters than in the field, while for the gas rich spirals and irregulars the reverse is the case (Oemler 1974).

Heating of the ICG has been considered by Ruderman and Spiegel (1971), Schipper (1974), and Lea and De Young (1976). While heating must be important in the case of highly supersonic motion, as the ICG passes through the bow shock of the galaxy, for transonic motion it is not. Lea and De Young found no heating at Mach numbers ≤ 2. This means that heating of the gas in the clusters to the observed temperature must be due to other processes. Infall from a more expanded state is a likely solution, although violent events in the central galaxy or galaxies may play a role. Most x-ray clusters do contain a dominant cD or radio galaxy (Bahcall, 1974). However, it is also possible that accretion of cooled gas into the galaxy may be responsible for the cD or radio properties (Silk, 1976).

In summary, the observations seem to favor the presence of a hot gas in rich clusters of galaxies, whose origin is partially in primordial matter which has collapsed into the cluster, and partially in gas lost from the galaxies. The gas is in a static (or almost static) equilibrium in the cluster, and is either tightly bound ($r_o <<$ cluster radius) or has an equation of state corresponding to $\gamma < 5/3$.

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