GAS IN GALAXY CLUSTERS

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Gaseous matter almost certainly cannot account for a significant amount of the binding mass in the cores of rich clusters. Implications of the variety of upper limits are well known (Tarter and Silk 1974), and will not be described here. However intracluster gas provides important clues to the evolution of galaxy clusters, and the present review is devoted to elucidating its role.

I. X-RAY OBSERVATIONS

X-ray data have provided the principal source of evidence for the existence of a hot intracluster gas. For some time, spectral fits to the continuum in the energy range 0.2 - 30 keV have marginally favored thermal as opposed to non-thermal (or power-law) intrinsic source spectra. Discovery of an emission feature at 7 keV, identified with Fe XXV and Fe XXVI line emission, has confirmed the presence of hot intracluster gas in four cluster sources (Mitchell *et al.* 1976; Serlemitsos *et al.* 1976; Mitchell and Culhane 1977). An unexpected finding is that the iron abundance is similar in at least three of the sources, and is generally within a factor of seven of the solar iron abundance. This latter conclusion appears to be moderately independent of various models for the gas distribution (Bahcall and Sarazin 1977). The inferred masses of gas are comparable to those within the luminous regions of the cluster galaxies, and only amount to a fraction (typically 10% in a hydrostatic model) of the cluster dynamical mass.

Recent observations with high spatial resolution (Gorenstein *et al.* 1977) indicate that the extended Virgo source is centered on M87 and is small (core radius approximately 100 kpc), and may therefore be confined by the gravitational potential well of M87 itself (Mathews 1977). Several other clusters are known to be extended sources of X-ray emission, typical core-radii being several hundred kpc (Kellogg and Murray 1974), usually larger than, or comparable to, the characteristic scale of the galaxy distribution. Gas temperatures based on X-ray spectral data are now available for some fifteen cluster sources (Jones and Forman 1977);

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there is a weak correlation with X-ray luminosity, the less luminous
source tending to have lower temperatures.

II. RADIO OBSERVATIONS

The morphology of tailed radio galaxies (TRG's) has provided dra-
matic evidence for the presence of intracluster gas. Most TRG's are as-
sociated with clusters; the few that are not (see below) may be associ-
ated with superclusters. There seems little doubt that the long (often
curved and typically several hundred kpc) tailed sources are produced
and maintained by interaction with the intracluster gas (Jaffe and Perola
1973; JP). Rudnick and Owen (1974) find that two-thirds of cluster radio
sources show significant amounts of distortion or misalignment, as com-
pared with the classical double-lobe structure. Common to the various
plasmoid ejection models is the confinement of the head of the TRG by
ram pressure:

$$p_{cr} + B^2/8\pi \lesssim \frac{1}{2}\rho v^2 \quad , \tag{1}$$

where B is the internal magnetic field, p_{cr} denotes the cosmic ray density
in the tail, ρ is the intracluster gas density, and v is the plasmoid
velocity relative to the intracluster gas. Use of the equipartition
field in the expanded tail region and conservation of flux to infer B(JP)
yields $\rho = 10^{-27}$ g cm^{-3} for 3C 129. This does not differ significantly
if the ejection is subsonic (Cowie and McKee 1975), but a substantially
lower value of ρ was inferred in a model where reacceleration of electrons
occurred in the tail (Pacholczyk and Scott 1976). In fact, this latter
conclusion is erroneous, as cosmic ray pressure was neglected in applying
(1). If turbulence – driven reacceleration of electrons is important and
results in fields below the equipartition value in the tail, the left
hand side of (1) is actually increased, and ρ is *larger* than in the JP
model. Ram pressure confinement generally leads to *minimum* densities
$\rho \sim 10^{-27}$ g cm^{-3}. This density is similar to the mean gas density found
in the case of X-ray clusters. The thermal pressure of the intracluster
gas is rather more model-dependent. If local acceleration occurs, no
constraint can be set on the gas temperature T. On the other hand, JP
argue from the constancy of the tail width that the thermal pressure
must balance the internal pressure in the tail, thereby enabling minimum
pressures of $\sim 10^{-11}$ dynes cm^{-2} to be inferred for the intracluster gas.
Tail curvature may reflect the galaxy trajectory, systematic gas flows
(such as cluster winds or infall), or buoyancy in the cluster potential
well.

Are there any TRG's outside rich clusters? Jaffe (1976) cites
several examples. However all are in or very near well-known super-
clusters, apart from "a clear cut example of a tailed source in a sparse
group of galaxies, that associated with NGC 7385". In fact, Murray *et
al.* (1977) find a nearby X-ray source (4U2259 + 16) in a region of "un-
usually high cluster density". The known TRG's outside rich clusters
might be in regions, such as superclusters, where diffuse hot gas is

present, and thermal confinement of the tailed source is therefore pos-
sible. The equipartition pressure in the case of NGC 7385 is a factor
∿100 lower than found for typical TRG's in rich clusters, amounting to
∿10^{-13} dynes cm^{-2} (Schilizzi and Ekers 1975). This is consistent with
confinement by an ambient gas of density ∿10^{-5} cm^{-3} at T ∿ 10^8 K (as
would be implied were the X-ray source identification correct).

The correlation between decametric spectral index and presence of a
radio source in an Abell cluster is well known, steeper spectral indices
being found in clusters. There are indications that the 26 MHz spectral
index steepens with increasing L_x (Erickson *et al.* 1977). The low fre-
quency data also indicate a correlation between the 26 MHz luminosity
L_{26} and L_x: for 14 cluster sources studied by Erickson *et al.*, one finds
d log L_x/d log L_{26} = 0.5 ± 0.3 (2σ). What perhaps is not as generally
appreciated is that the higher radio frequency data show an equally good
correlation. Utilizing the 1400 MHz survey of Owen (1975), one finds
that d log L_x/d log L_{1400} = 0.7 ± 0.3 (2σ) for 24 cluster sources.

III. OPTICAL DATA

The apparent correlation between X-ray luminosity and cluster mor-
phological type may largely be due to a correlation between L_x and cluster
richness (R) (Jones and Forman 1977). The data on some 36 X-ray cluster
sources can be fitted by d log L_x/dR = 0.23 ± 0.13 (2σ). Bahcall (1977*a*)
finds a similar correlation between L_x and central counts of galaxies.

Melnick and Sargent (1977) find that the radial distribution of
spirals often differs from that of ellipticals and S0's in X-ray
clusters. The ratio of spiral to disk systems decreases, and the ellip-
tical fraction increases, with increasing L_x. The spiral fraction also
decreases with increasing velocity dispersion Δv. In a larger sample of
14 clusters, Bahcall (1977*b*) confirms that the fraction of spiral
galaxies decreases with L_x.

The weak correlation between L_x and Δv has persisted (but not
strengthened) as more data has become available (Faber and Dressler 1976).
One presently has, for 13 X-ray clusters with measured Δv, d log Δv/d
log L_x = 0.13 ± 0.08 (2σ).

Another form of optical evidence for diffuse intracluster matter
is due to intergalactic bridges and filaments. The diffuse light in the
Coma cluster is the best studied example of this sort, but appears to
largely consist of blue stars (Thuan and Kormendy 1977, and references
cited therein). The interpretation of quasar absorption lines still
arouses sufficient controversy that they will not be cited here as pro-
viding any unambiguous evidence for the existence of intracluster gas,
theoretical arguments notwithstanding (e.g. Silk 1970).

IV. IMPLICATIONS

The near-solar abundances of iron in at least four X-ray cluster sources appears to have eliminated pure infall models of cluster evolution; detailed spatial mapping is still needed to confirm this conclusion. One aspect of these early models has survived: infall through the gravitational potential well of the galaxy cluster remains the best candidate for supplying the thermal energy of the gas (Silk 1973). The near coincidence between cooling and Hubble times in the cluster cores can be understood if cooling regulates the amount of gas present, the gas being accreted onto the most massive, slowly moving central galaxies (and possibly initiating the formation of these systems) (Silk 1976; Cowie and Binney 1977). This could account for the frequency of occurrence of cD galaxies in luminous X-ray clusters (where more gas may have initially been present). If this infall occurred sufficiently long ago, no evidence of recent star formation may remain in the galaxy colors. The dominant galaxies might actually end up being reddened if preferentially enriched material has been accreted. One might expect that the colors of cD galaxies should not fall on a simple linear extrapolation of the galaxy color-magnitude relation.

The gas density in the cluster core $\simeq T^{1/2}$, whence we expect that at photon energy ε, $dL_x/d\varepsilon \simeq T^{1/2} \exp(-\varepsilon/kT)$. This relation is consistent with current data.

The correlation both of low (26 MHz) and high (1400 MHz) frequency radio fluxes with L_x can be simply understood if the magnetic fields in the extended radio sources (that may be largely contributing to L_R: Aizu 1977) originated together with the enriched intracluster gas. Assume that the relativistic electron density is maintained in equipartition with the intracluster field. This may not be implausible since local acceleration mechanisms are evidently required. Suppose that the intracluster magnetic fields and relativistic particles are initially produced by galactic supernova remnants. Since the rate at which enriched gas is produced by evolving stars should be proportional to the supernova rate, one would expect that the total cosmic ray electron energy E_{el} is approximately proportional to the gas mass M_{gas}. Consequently one obtains (assuming similar volumes for the X-ray and radio sources) $L_R \propto L_x (E_{el})^2 (M_{gas})^{-2} (\Delta v)^{-1}$. This suggests a proportionality similar to that observed (since $L_x \simeq (\Delta v)^4$).

If equipartition is attained, the magnetic field strength should be proportional to $E_{el}^{1/2} r^{-3/2}$ (where r is the source dimension). Ignoring any variation in r, the synchrotron lifetime t_s (at a fixed frequency) varies as $E^{-3/4}$, or $M_{gas}^{-3/4}$ in the protogalactic infall model. Since $L_x \propto M_{gas}^{5/2}$, a shorter electron lifetime $t_s \simeq L_x^{-3/10}$ (and therefore steeper radio spectrum) is indicated in high luminosity X-ray clusters.

The decrease of spiral content with L_x and Δv supports ram pressure stripping (Gunn and Gott 1972) as the mechanism for converting spirals to SO's. A quantitative estimate of its significance can be obtained in

individual clusters where spiral galaxies that pass within a critical
radius r_s of the cluster centre (core radius r_c) are stripped (Tarter

Cluster	r_s/r_c	$\chi^2_{min}(DF^*)$ (r_s model)	$\chi^2_{min}(DF^*)$ (King model)	Δv (km s^{-1})	r_x/r_c
Abell 262	2.4	0.34(7)	8.8(7)	760	(6.0)
326	2.0	0.19(9)	12.5(9)		
426	5.3	14.5(21)	42.7(21)	2420	0.91
576	1.2	1.2(12)	6.5(12)		
1060	2.2	13.6(12)	25.9(12)	1335	> 0.85
1656	5.3	0.16(4)	6.9(4)	1560	2.5
2666	0.6	0.47(8)	0.57(8)		
Virgo	1.4	0.99(15)	7.2(15)	1070	0.38

*Deg. freedom.

1977). The absence of spirals within the central regions satisfactorily
fits the data of Melnick and Sargent (1977), whereas the fit to the
radial distribution of spirals with a uniform (King) distribution is
significantly worse (except for Abell 2666, where $r_s < r_c$). X-ray core
radii (r_x) generally appear to be $\lesssim 0.5$ r_s (except for Abell 262, where
r_x is poorly determined), indicating that ram pressure stripping is ef-
fective until the gas density has dropped to about ~ 0.1 of its central
value. The ratio r_s/r_c is low for three clusters with low velocity
dispersion (Δv), and larger for the two clusters with high Δv. The ram
pressure stripping model predicts such correlations: r_s should scale
both with r_x, and as $\Delta v^{4/3}$ (for $r_s > r_c$). More data on r_x and Δv would
help establish whether these indications of correlations are correct.
The decrease of spiral content with Δv and L_x provides further support
for ram pressure stripping.

Richness is a logarithmic measure of counts of luminous galaxies
within an Abell radius, and may be taken to give a measure of cluster
optical luminosity $L_{c\ell}$ (since cluster core radii show small variations):
specifically, $R \approx 2.1 \ln (L_{c\ell}/L_0)$. If we assume a relation of the form
d log L_x/dR = β ($\beta = 0.23 \pm 0.13$; § III), then $L_x \propto L_{c\ell}^{5.1\beta}$. With $M_{gas} \propto$
cluster mass $M_{c\ell}$, one finds that $M_{c\ell} \propto L_x^{2/5} \propto L_{c\ell}^{2\beta} \propto L_{c\ell}^{0.46}$. Other
functional fits to L_x(R) also yield a weak dependence of $M_{c\ell}$ on $L_{c\ell}$.
Hence $M_{c\ell}/L_{c\ell}$ decreases with increasing richness, and $\Delta v \propto (1.6)^{\beta R}$.
Measurement of cluster velocity dispersions (and masses) would enable us
to verify whether $M_{gas} \propto M_{c\ell}$ for X-ray clusters where M_{gas} cannot be
determined directly.

The available data (for five sources) is consistent with $\mu(\Delta v)^{2/3} \approx$
kT (where μ is the mean molecular weight), expected in most thermal
models (Silk 1973). The weak (L_x, Δv) correlation (Solinger and Tucker

1972) is presently incapable of distinguishing between different theoret-
ical models; this situation may change when improved X-ray source size
data becomes available, and can be incorporated into a search for a more
general correlation.

Inverse Compton X-radiation, produced by scattering of the microwave
background radiation by relativistic electrons, seems to account only for
a small fraction of the observed fluxes, since the iron-line data and
limits on hard X-ray fluxes indicate that most of the emission must be
thermal. One would also expect that the correlation between L_x and L_R
should improve towards lower radio frequencies (Harriss and Romanishin
1974). A correlation between L_x and n (Gould and Raphaeli 1977), utiliz-
ing the predicted decrease in the microwave background radiation towards
rich clusters (Sunyaev and Zel'dovich 1972), should be potentially cap-
able of directly discriminating between and non-thermal models; however
it is presently inconclusive, recent results (Lake and Partridge 1977;
Rudnick 1977) having failed to confirm earlier indications of a positive
effect (Gull and Northover 1976) in known X-ray clusters. There are
indications, however, of the "cooling" effect in very rich clusters.

Nevertheless, inverse Compton X-rays are bound to be important in
nearby clusters at photon energies $\gtrsim$ 30 keV, and also in distant clusters
at $z \gtrsim 1$ (e.g. Rees 1967). Assuming equipartition field strengths, the
ratio of inverse Compton to thermal X-ray fluxes is $L_x^{ic}/L_x^{th} \approx 0.01 (1+z)^4$
$[M_{gas}(z)/M_{gas}(0)]^{-1}$. If the gas mass does not change with time, non-
thermal X-rays will dominate at $z \gtrsim 1.5$. The gas mass cannot exceed the
dynamical cluster mass, typically $\sim 10 M_{gas}(0)$: hence inverse Compton X-
rays *must* dominate at $z \sim 4$.

V.   ORIGIN AND EVOLUTION

The gradual increase of the elliptical to disk galaxy content of
clusters with increasing L_x and decreasing Bautz-Morgan type suggests
that the morphological distribution of galaxy types may be determined
when the cluster forms. This is not a unique interpretation, but a
possible explanation may be that galaxies undergo strong mutual inter-
actions when clusters form. This can only occur to any significant extent
if the galaxies are themselves newly formed protogalaxies. Thus we come
to one of the crucial unresolved issues of galaxy formation theories:
do galaxies form long before, or more or less coevally with, clusters?

The gas content of clusters leads support to the notion of coeval
formation. The amount of enriched intracluster gas attests to its
protogalactic origin: current mass loss rates fail to account for it.
If galaxies formed in isolation, one might expect the stellar content
to rapidly dominate over the gas content as star formation proceeds,
just as happens when the disks of spiral and SO galaxies are formed. In
rich clusters, this process cannot have occurred, for some $10^{11} M_\odot$ per
galaxy is present in the form of *enriched* intracluster gas. This amount
of matter is comparable to a typical disk mass. While ordinary spirals

develop in isolation, it seems plausible that cluster galaxies must be
inhibited from making enriched stellar disks by interacting with neigh-
boring galaxies (cf. Ostriker 1977). One can account for intracluster
gas if the enriched matter produced by ordinary stellar evolution in
protogalaxies stays in gaseous form (De Young 1977): only if coeval
formation of galaxies and clusters occurs does this seem easy to arrange.

There are several mechanisms by which protogalactic interactions
can affect galactic evolution. The most important may be due to col-
lisions, which will be frequent between protogalaxies in newly formed
clusters (Silk 1977). Initially, relative encounter velocities may be
low, and coalescence can occur. Once protogalaxies have fallen through
the cluster potential well, after roughly a crossing time ($\sim 10^9$ yr) has
elapsed, the encounter velocities in rich clusters will be large compared
to the internal motions within the protogalaxies. While the protogalaxies
are largely gaseous, subsequent collisions will be highly disruptive.
Diffuse protogalactic gas will be shock heated, and escape from the proto-
galaxies, but dense clouds will cool effectively, and remain bound to
the protogalaxy. If the clouds are initially near the Jeans mass, the
shock passage will trigger star formation.

Star formation will result in the production of enriched material,
which will be ejected by supernova-driven wind flows from the less mas-
sive galaxies into the intracluster medium. Evaporation (Cowie and
Songaila 1977) and ram pressure may also play a role. More massive
galaxies will be capable of retaining supernova ejecta, and make succes-
sive generations of stars. Galaxies of mass $\lesssim 10^{11}$ $M_\odot$ may provide most
of the intracluster gas, and should be relatively unenriched (and bluer)
compared to much more massive systems. The metal abundance of gas in
the cluster core is expected to approach that of the most massive cluster
galaxies.

How can these speculations be verified? X-ray cluster galaxies
should have undergone more recent star formation than other clusters,
and this should be reflected in their colors, particularly at $z \gtrsim 1$,
where the cluster gas fraction (and therefore infall and ram pressure
effects) may be enhanced. The color changes should exceed those expected
on the basis of theories of the evolution of isolated galaxies. L_x
should be larger by a factor $\sim$ (present gas fraction)$^{-2}$. Measurements
of the spatial distribution of line emission will help elucidate the
role of galaxy interactions. To distinguish between theoretical models,
a multiparameter analysis is needed that incorporates the principal
X-ray, optical, and radio parameters. This should become feasible with
the new generation of X-ray satellites.

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DISCUSSION

Gisler: Further evidence with regard to the ram pressure stripping of cluster galaxies may be obtained by looking at the gas content of cluster galaxies. I have just completed a study of emission line frequencies in a large sample of optical galaxy spectra, obtained from a literature survey covering the last twenty years (approximately 1300 galaxies), and I have found that the frequency of the emission line objects is indeed much lower in the Zwicky compact clusters than in less compact associations (Gisler 1977, submitted to *Mon. Not. R. astr. Soc.*).

Abell: What is the basis of the 10^{14} $M_\odot$ of evolved matter that had to be ejected?

Silk: X-ray observations, in particular of the Perseus and Coma clusters, can be fitted satisfactorily by a range of thermal models that determine the total mass of X-ray emitting gas to within a factor or roughly 3. In the simplest isothermal models, the central density is typically $\sim 3 \times 10^{-3}$ cm^{-3}, and the X-ray core radius is ~ 0.5 Mpc.

Ostriker: Incidentally, in the galactic evolution models, you get about 10 $M_\odot$ ejected per unit solar luminosity and hence if the luminosity of the cluster is 10^{13} $L_\odot$, you get 10^{14} $M_\odot$ ejected.

Tinsley: There is plenty of evidence for blue galaxies in clusters in the redshift interval 0.5 to 1.0 which will be discussed in my talk on Thursday.

Parijskij: I would like to mention our new results which we have obtained concerning the Sunyaev-Zeldovich effect in the Coma cluster. We first observed a small dip in the microwave background radiation in the direction of the Coma cluster in 1970 and several later observations give similar positive results but with large errors. Our latest observations were made with the 600-metre RATAN radio telescope at a wavelength of 4 cm. We have again observed a dip in the direction of the Coma cluster having $\Delta T/T = -2 \times 10^{-4} \pm 0.7 \times 10^{-4}$ K and we have an estimate of its angular size. It is somewhat less than the size of the X-ray source in the cluster but we are not certain if the difference is significant or, if real, whether it is due to a temperature or a density effect.

Boynton: This result for the Coma cluster is consistent with zero at the two-sigma level and is therefore consistent with the very recent measurement of G. Lake and R. B. Partridge at $\lambda = 9$ mm:

$$\Delta T/T < 0.05 \pm 0.05.$$

However, this latter limit implies no significant indication of the Sunyaev-Zeldovich effect at an even lower level of significance for this particular cluster.

Zeldovich: Observers should also try to see the effect beyond the maximum of the spectrum of the microwave background radiation where a corresponding small <u>increase</u> in the temperature of the radiation in the direction of the Coma cluster should be observed. It is, however, a very difficult observation but we need to be sure about it!