Mon. Not. R. astr. Soc. (1979) **186**, 783–790

The evolution of X-ray emitting gas in clusters of galaxies

A. C. Fabian and P. E. J. Nulsen *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

Received 1978 August 16; in original form 1978 July 5

Summary. We study the bremsstrahlung cooling process in X-ray clusters using a simple model. Only for a restricted range of initial conditions can the atmospheres in rich clusters of galaxies have undergone substantial cooling without leaving excessive present X-ray luminosities. From observational data we then find that it is unlikely that clusters can have gone through a high-temperature cooling phase since $z = 3$. We conclude either that clusters of galaxies must have formed with little gas in their cores or that such gas was dispersed before cooling occurred.

1 Introduction

X-ray observations of extended emission from clusters of galaxies (e.g. Lea *et al.* 1973; Gorenstein *et al.* 1977), together with X-ray spectra (particularly Mitchell *et al.* 1976; Serlemitsos *et al.* 1977) and correlations with galaxy content (Bahcall 1977a, b; Jones & Forman 1978; McHardy 1978), indicate the presence of hot intracluster gas in many (and possibly all) clusters. The quantities of such gas in the cores of these clusters are less than a few per cent of the binding masses inferred from galaxy motions. Significant amounts of cooler gas are not present (see, e.g. Tarter & Silk 1974). Here we study this apparent lack of gas in clusters, and investigate the possibility that more substantial amounts of gas have existed in the past which have subsequently cooled to form both stars and some proportion of the dark binding mass.

Most previous work on the evolution of gas in clusters has been based upon numerical hydrodynamical calculations (Lea 1974; Gull & Northover 1975; Takahara *et al.* 1976; Perrenod 1978) and has investigated only a small region of the available parameter space. The occurrence of strong cooling in the cluster cores is usually dismissed. This seems a reasonable approach when it is considered that the cooling-time of the observed cores is currently $\gtrsim H_0^{-1}$, but, of course, such a cooling-time is also likely to be found in any gas remaining after a cooling phase. In Section 2 we present an approximate technique for estimating the evolution of cluster gas over a wide range of initial conditions. We find that strong cooling could have taken place for a certain range of these conditions.

We then use observations of the X-ray background in Section 3 to limit the X-ray luminosity function of clusters as a function of redshift. Combining this result with our model of cluster evolution, we constrain the number of clusters that can have passed through a cooling phase since a redshift of 3. This leads us to conclude that extensive cooling in hydrostatic atmospheres has never occurred in rich clusters of galaxies.

Finally we discuss alternative means by which clusters may have rid themselves of gas without complete cooling having occurred.

2 The cooling of gas

X-ray measurements of those clusters which have been studied in detail indicate that the intracluster gas (assumed unclumped) is, in general, cooling on a time-scale $t_c \gtrsim H_0^{-1}$. Many authors have therefore modelled the gas as a hydrostatic atmosphere established in the cluster potential-well (e.g. Gull & Northover 1975; Lea 1976; Cavaliere & Fusco-Femiano 1976, 1978). Ignorance of the manner in which such an atmosphere originated is parametrized by a 'polytropic' index γ ($p \propto \rho^\gamma$), central temperature T_0 and central number-density n_0 for the gas. The current observational data (both spectral and spatial) do not warrant a more elaborate model, and three parameters are adequate.

γ is assumed to lie between 5/3 and 1, with convection occurring if the upper bound is exceeded. A particular value of γ throughout an atmosphere is, in a sense, a measure of the history of heat input (due to infall, conduction etc.) as a function of radius. There is little reason to suppose that real atmospheres fit such a model in detail. Since the core region dominates the X-ray emission of the cluster, the X-ray properties are relatively insensitive to γ. The assumption that the gas is hydrostatic is reasonable since the time for sound to cross the core is $\sim 3 \times 10^8$ yr and $\ll H_0^{-1}$ (we adopt $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$).

The central temperature, T_0, may be regarded as a measure of the depth of the gravitational potential well into which the gas has fallen. We define the 'virial' core temperature, T_v, by:

$$\frac{kT_v}{\mu m_H} = |\phi(r=0)|,$$

where $\phi(r)$ is the gravitational potential of the cluster, and μm_H is the mean mass per particle. The hot gas extends to infinity if $T_0 > [(\gamma - 1)/\gamma]\, T_v$. All values of T_0 are in principle possible, but the total mass of gas within the cluster diverges rapidly as T_0 approaches $[(\gamma - 1)/\gamma]\, T_v$. Current values of n_0 must be made small enough that, with T_0, they yield a luminosity and spectrum similar to those observed: in general $T_0 \sim 10^8$ K and $n_0 \sim 10^{-3}\,\mathrm{cm^{-3}}$. This density is ~ 1 per cent of that required to bind a cluster core gravitationally (Rood *et al.* 1972).

We consider the evolution of an initially hydrostatic atmosphere. Convective stability requires that the entropy is a non-decreasing function of radius, and thus so is

$$\Sigma = T^{3/2}/n,$$

where T is the gas temperature and n its density. The bremsstrahlung cooling time $t_c \sim T^{1/2}/n \sim \Sigma^{3/5} p^{-2/5}$ and thus, since $dp/dr \leqslant 0$, $dt_c/dr \geqslant 0$. Cooling hence occurs first in the core, then proceeds outwards. Gas from larger radii moves into the volume initially occupied by the gas which has cooled, but, owing to the rapid increase of volume with radius, most of the remaining gas is only perturbed slightly (i.e. the flow time-scale $\simeq$ the time-scale for local cooling). The luminosity evolution can then be approximated by the rate at which gas cools in a static atmosphere. If we assume that the gas radiates all its thermal energy instantaneously at t_c then

$$L_X(t) = \alpha \left(\frac{dM}{dt}\right)\bigg|_{r=r_c} \frac{kT_c}{\mu m_H}, \qquad (1)$$

where we define r_c such that, in the initial atmosphere, $t_c(r_c) = t$ ($t = 0$ initially), with $T_c = T(r_c)$ and

$$\left(\frac{dM}{dt}\right)\bigg|_{r=r_c} = \frac{4\pi r_c^2 \mu m_H n(r_c)}{(dt_c/dr)|_{r=r_c}}. \qquad (2)$$

The quantity α takes account of flow details and is of order unity (numerical hydrodynamic calculations indicate that $\alpha < 10$). A better approximation, especially at early times, is L'_X/α, made by subtracting from the total luminosity of the atmosphere the luminosity of the gas which has cooled. This assumes that the gas at each radius emits its thermal energy over a time t_c. Beyond the core, $L'_X \simeq L_X$. We have calculated L'_X/α for various polytropic atmospheres with a gravitating mass distribution

$$\rho(r) = 2.4 \times 10^{-25} [1 + (r/240\,\mathrm{kpc})^2]^{-3/2}\,\mathrm{g\,cm^{-3}} \qquad (3)$$

(*cf.* Rood *et al.* 1972), for various n_0, T_0 and γ. The results for $\gamma = 5/3$ and 1 and a total elapsed time of H_0^{-1} are plotted in Figs 1(a) and (b).

Less than 10 per cent of all Abell clusters have present X-ray luminosities greater than 10^{44} erg/s (Jones & Forman 1978; McHardy 1978). It is then immediately apparent from Fig. 1 that n_0 can never have been much above $\sim 10^{-3}\,\mathrm{cm}^{-3}$ at the base of a substantial hydrostatic atmosphere in most rich clusters. Only by reducing T_0, with $\gamma \sim 5/3$, thereby terminating the atmosphere at small radii, can acceptable luminosities occur now for larger values of n_0.

Although these results were obtained for a specific model atmosphere it can be seen from equations (1) and (2) that for a bounded atmosphere the peak luminosity, which occurs as the gas in the core cools, depends sensitively only on n_0, T_0 and the core radius (see Section 3). The core radius appears to be relatively constant for rich clusters (Bahcall 1977c) and is thus not a free parameter. We conclude that, in general, either n_0 always $\lesssim 10^{-3}\,\mathrm{cm}^{-3}$, or n_0 was sufficiently large and the atmosphere sufficiently small ($T_0 \lesssim 10^8$ K) that most of it has cooled before the present. The 'barrier' between the two alternative models occurs because, if $n_0 \sim 3 \times 10^{-3} T_8^{1/2}\,\mathrm{cm}^{-3}$, gas in the core is cooling now, producing luminosities exceeding those commonly observed.

Detailed studies of those parts of an atmosphere that have begun to cool require strictly a time-dependent hydrodynamic calculation. We expect, however, that the quasi-steady state flows discussed by Cowie & Binney (1977), Fabian & Nulsen (1977) and Mathews & Bregman (1978) then apply. Outside these regions the atmosphere is perturbed only slightly from its initial form.

3 Observational limits on the luminosity function and cooling

Since the present X-ray luminosities do not exclude the possibility that clusters have passed through a cooling phase, we now ask whether useful constraints can be placed on their behaviour in the past.

We define the integral X-ray luminosity function of clusters, $N(>L, <z)$, as the number of sources per steradian with intrinsic luminosity $>L$ and redshift $<z$. Then, assuming clusters all to have a thermal bremsstrahlung spectrum with $kT = 10$ keV, we calculate their

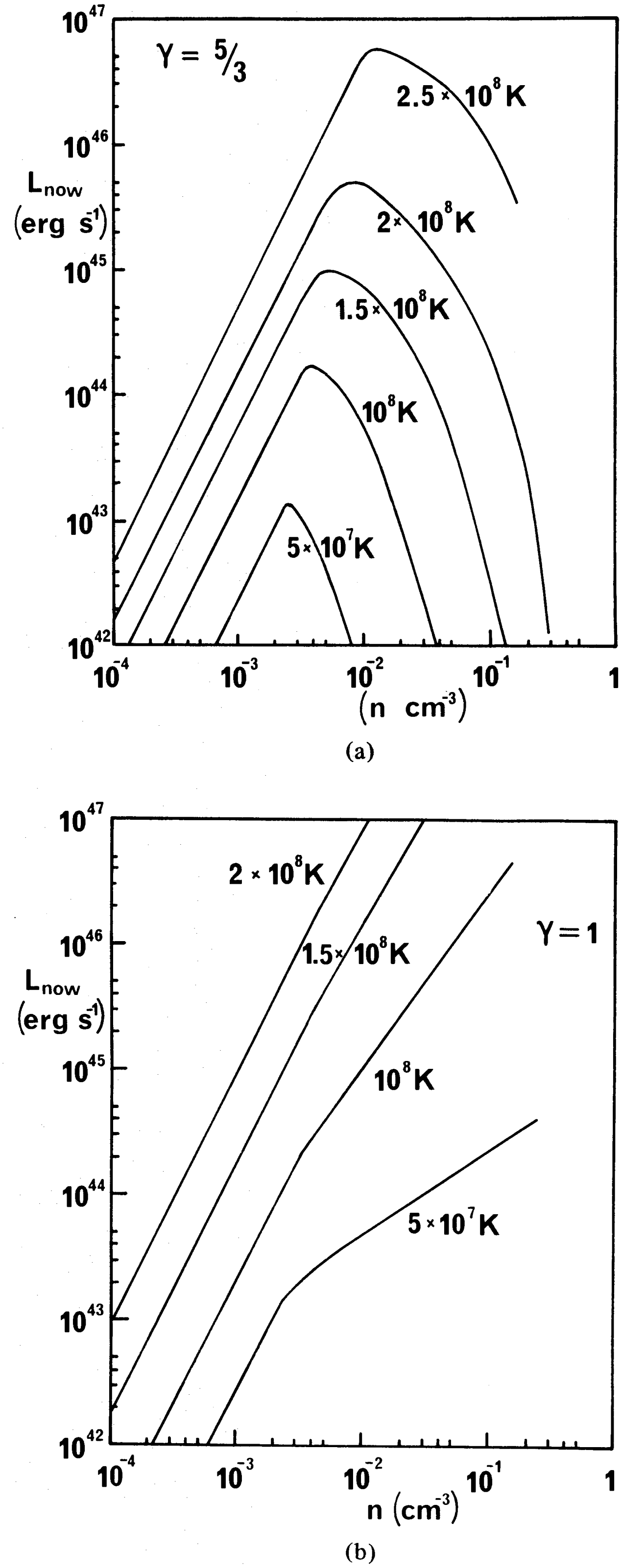


Figure 1. (a, b) X-ray luminosity now (divided by α) as a function of initial central density for a set of atmospheres in the gravitational potential of the mass distribution $2.4 \times 10^{-25}[1 + (r/240\,\mathrm{kpc})^2]^{-1.5}\,\mathrm{g\,cm^{-3}}$. Curves are labelled with their initial central temperature T_0. The quantity α allows for the details of the cooling and inflow processes and is expected to be >1. In Fig. 1(a) $\gamma = 5/3$, and in (b) $\gamma = 1$. Note that the temperature obtained by fitting X-ray data with a single temperature spectrum is a measure of T_0 when $\gamma = 1$, but underestimates T_0 (by a factor of ~ 2–3) when $\gamma = 5/3$.

2–6 keV flux at the Earth, $S(L, z)$, as a function of L, z and q_0 (using a Friedmann cosmological model). The results are not sensitive to the assumption of a standard spectrum which we use throughout this section.

From observations it is possible to place limits, $N_L(S)$, on the integral source counts, $N(>S)$, for any value of S. Firstly, any distant extragalactic sources with $S(L, z) \gtrsim 0.6$ cannot be more numerous than the unidentified sources at high galactic latitudes, i.e.

$$N_L(S) = 5 S^{-3/2}\,\mathrm{sr}^{-1}, \quad S > 0.6, \tag{4}$$

where S is in *Uhuru* count/s. Secondly, the fluctuation in the background due to faint sources (individually undetectable) must not exceed ~1 per cent of the background (Fabian & Rees 1978), so that

$$N(>S) < 3.8 S^{-2}, \quad S < 0.6. \tag{5}$$

Finally the total background flux must not be exceeded (Fabian & Rees 1978),

$$N(>S) < 2.2 \times 10^3 S^{-1}. \tag{6}$$

Now

$$N(>L, <z) < N_L[S(L, z)]. \tag{7}$$

The limits on $N(>L, <z)$ resulting from combining equation (7) with (6), (5) and (4) are plotted in Fig. 2 for $q_0 = 0.05$ and 0.5. The upper dashed curve in each case is the total number of Abell clusters sr^{-1} normalized to $4 \times 10^5 (c/H_0)^{-3}$ (Rowan-Robinson 1972).

To produce the 2–6 keV X-ray background without violating the limits on the fluctuations requires $\gtrsim 10^6$ source sr^{-1} (Fabian & Rees 1978). This implies that it does not originate predominantly in rich clusters of galaxies.

In order to place limits on the past evolution of cluster atmospheres, we estimate the minimum peak luminosity of an atmosphere cooling at cosmic time t. The peak luminosity for any bounded atmosphere is given by

$$L_{\mathrm{peak}} = \alpha(M_{\mathrm{core}}/t_{\mathrm{cool}})(kT_0/\mu m_{\mathrm{H}}), \tag{8}$$

where α is again of order unity, M_{core} is the mass of gas in the core ($\propto n_0 a^3$ where a is the core radius), and t_{cool} is the cooling time at the cluster centre. Furthermore, an atmosphere cooling at time t must have $t_{\mathrm{cool}} < t$ and thus $n_0 > KT_0^{1/2} t^{-1}$, where K is a constant. Thus, for $a = 240$ kpc, we find

$$L_{\mathrm{peak}} \gtrsim L_{\mathrm{m}}(t) = 2.5 \times 10^{45} T_8^{3/2} (t_0/t)^2\,\mathrm{erg/s}, \tag{9}$$

where $T_0 = 10^8 T_8$ K and $t_0 = H_0^{-1}$. The constant of proportionality was determined from numerical hydrodynamic models (giving $\alpha \simeq 10$). The numerical calculations also show that the X-ray luminosity remains at about L_{peak} for a time $\sim t_{\mathrm{cool}}/3$ after the start of cooling.

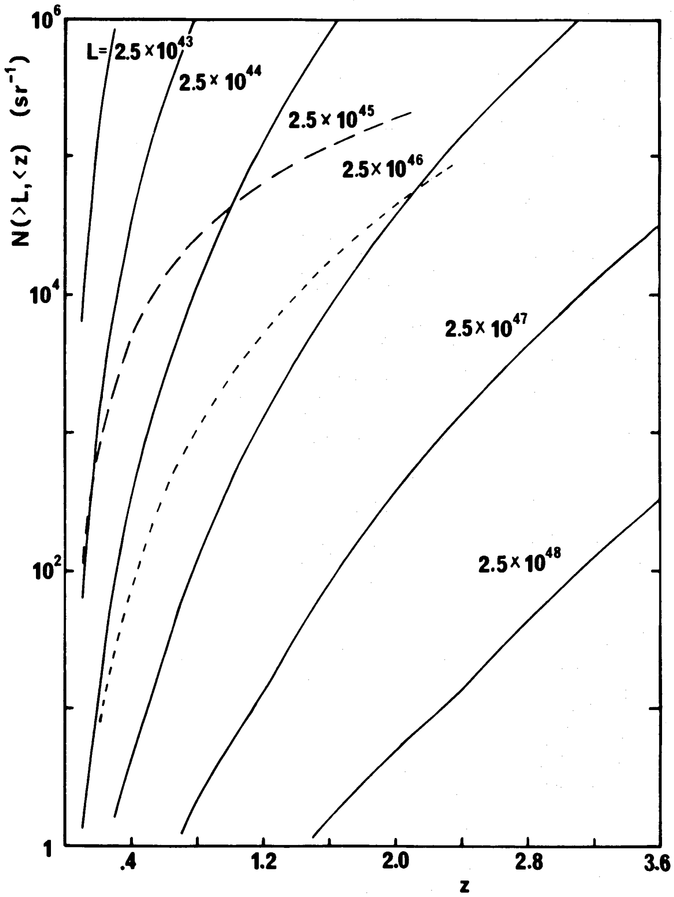
We can now calculate the minimum 2–6 keV flux at the Earth, $S_{\mathrm{min}}(z)$, from a cluster at its peak luminosity if it reaches that peak more recently than $t(z)$:

$$S_{\mathrm{min}}(z) = S[L_{\mathrm{m}}\{t(z)\}, z]. \tag{10}$$

The number of clusters which can have cooled since z is then limited, using equations (4), (5) and (6), by

$$N_{\mathrm{cooled}}(<z) \leqslant N_L[S_{\mathrm{min}}(z)], \tag{11}$$

where $N_{\mathrm{cooled}}(<z)$ is the number of clusters which have started cooling at redshifts $<z$. For $z \leqslant 3$, the correction to inequality (11) due to finite duration of the cooling phase is less



(a)

Figure 2. (a, b) Limits on the integral X-ray luminosity function versus redshift. The solid curves give the maximum number of sources sr^{-1} (with $kT = 10\,keV$), with redshift less than z and luminosity greater than L (in erg/s) compatible with observations of the X-ray background. The upper dashed curves are the total number of Abell clusters sr^{-1} normalized to $4 \times 10^5 (c/H_0)^{-3}$. The lower dashed curves give the maximum number of clusters which can have passed through a cooling phase since z (see text). For Fig. 2(a), $q_0 = 0.05$ and for (b), $q_0 = 0.5$.

than a factor of 2 and has been neglected. $N_L[S_{\min}(z)]$ is shown in Fig. 2 as the lower dashed curve.

It is clear that a substantial fraction of all rich clusters cannot have gone through a cooling phase since $z \simeq 2$. This is a fairly strict upper limit so we conclude that it is unlikely (impossible for $q_0 \gtrsim 0.5$) that the gas in any rich cluster has undergone substantial cooling since $z \simeq 3$; it then follows that such clusters formed with very little gas in their cores.

4 Discussion and conclusions

We have shown that the inner region of rich clusters of galaxies can never have contained much gas (more than a few per cent of the binding mass) that has cooled at X-ray temperatures. Thus rich clusters of galaxies are unlikely ever to have contained massive hydrostatic atmospheres. We cannot, however, draw firm conclusions about the amount of gas in the outer parts of clusters, where $t_c \gg H_0^{-1}$.

Our conclusions on cluster cores may be relaxed if the gas cooled at a lower temperature, such as when the cluster was in the process of forming. This is consistent with the model for cluster formation of Doroshkevich, Sunyaev & Zel'dovich (1974), but still requires a high efficiency for the formation of stars or of dark matter, such that but a few per cent remain

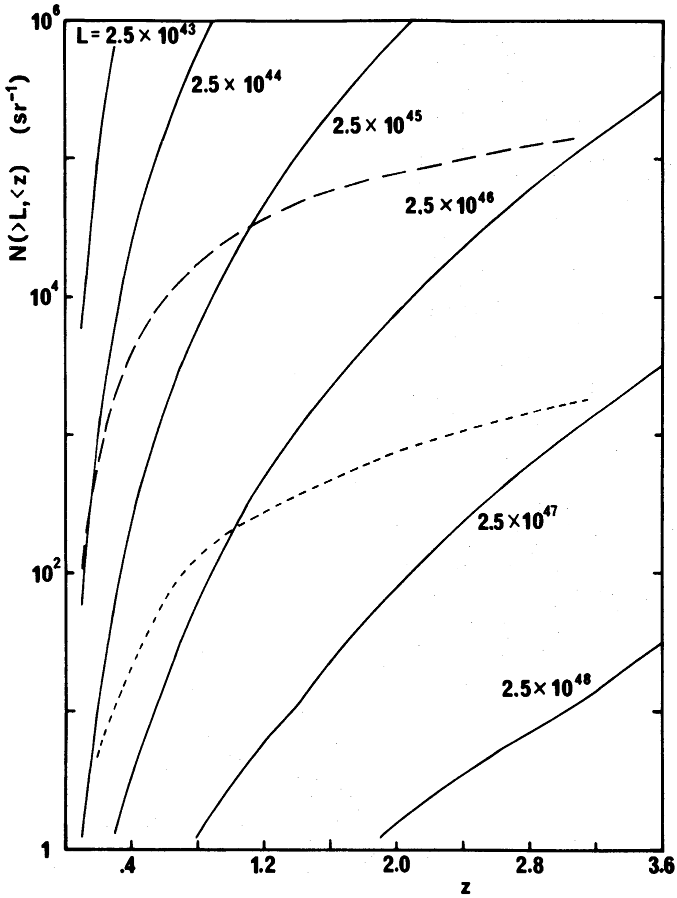


Figure 2 (b)

as gas. A second alternative which can overcome this problem is an early phase of star formation (at $z \sim 100$) followed by hierarchical clustering (White & Rees 1978). At an early epoch the gas density might be high enough to make star formation much more efficient than at a later stage.

An ejection or outflow mechanism is a further plausible means for reducing the amount of gas in clusters. The supernova rate may have been sufficiently high during the early phases of star formation that most of the gas was ejected from the cores of clusters (Schwarz, Ostriker & Yahil 1975; Fabian & Rees 1978). This process could perhaps also be related to the formation of the dark matter constituting most of the binding mass in clusters, particularly if it consists of compact objects.

Acknowledgments

ACF acknowledges the Radcliffe Trust for support and PEJN acknowledges receipt of a Hackett Studentship from the University of Western Australia. We thank Len Cowie for useful comments.

References

Bahcall, N. A., 1977a. *Astrophys. J.*, **217**, L77.
Bahcall, N. A., 1977b. *Astrophys. J.*, **218**, L93.
Bahcall, N. A., 1977c. *A. Rev. Astr. Astrophys.*, **15**, 505.
Cavaliere, A. & Fusco-Femiano, R., 1976. *Astr. Astrophys.*, **49**, 137.

Cavaliere, A. & Fusco-Femiano, R., 1978. Preprint.

Cowie, L. L. & Binney, J., 1977. *Astrophys. J.*, **215**, 723.

Doroshkevich, A. G., Sunyaev, R. A. & Zel'dovich, Y. B., 1974. In *Confrontation of Cosmologica Theories and Observation*, p. 213, ed. Longair, M. S., D. Reidel, Dordrecht, Holland.

Fabian, A. C. & Nulsen, P. E. J., 1977. *Mon. Not. R. astr. Soc.*, **180**, 479.

Fabian, A. C. & Rees, M. J., 1978. *Mon. Not. R. astr. Soc.*, **185**, 109.

Gorenstein, P., Fabricant, D., Topka, K., Tucker, W. & Harnden, F., 1977. *Astrophys. J.*, **216**, L95.

Gull, S. F. & Northover, K. J. E., 1975. *Mon. Not. R. astr. Soc.*, **173**, 585.

Jones, C. & Forman, W., 1978. *Astrophys. J.*, **224**, 1.

Lea, S. M., 1974. *PhD thesis*, University of California at Berkeley.

Lea, S. M., 1976. *Astrophys. J.*, **203**, 569.

Lea, S. M., Silk, J. I., Kellogg, E. & Murray, S., 1973. *Astrophys. J.*, **184**, L111.

McHardy, I., 1978. *Mon. Not. R. astr. Soc.*, **184**, 703.

Mathews, W. G. & Bregman, J. N., 1978. *Astrophys. J.*, **224**, 308.

Mitchell, R. J., Culhane, J. L., Davison, P. J. N. & Ives, J. C., 1976. *Mon. Not. R. astr. Soc.*, **176**, 29P.

Perrenod, S. C., 1978. Preprint.

Rood, H. J., Page, T. L., Kintner, E. C. & King, I. R., 1972. *Astrophys. J.*, **175**, 627.

Rowan-Robinson, M., 1972. *Astr. J.*, **77**, 543.

Schwarz, J., Ostriker, J. P. & Yahil, A., 1975. *Astrophys. J.*, **202**, 1.

Serlemitsos, P. J., Smith, B. W., Boldt, E. A., Holt, S. S. & Swank, J. H., 1977. *Astrophys. J.*, **211**, L63.

Takahara, F., Ikeuchi, S., Shibazaki, N. & Hoshi, R., 1976. *Prog. Theor. Phys.*, **56**, 1093.

Tarter, J. & Silk, J., 1974. *Q. Jl R. astr. Soc.*, **15**, 122.

White, S. D. M. & Rees, M. J., 1978. *Mon. Not. R. astr. Soc.*, **183**, 341.