X-RAYS FROM ELLIPTICAL GALAXIES

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ABSTRACT. X-ray observations have shown that early-type galaxies contain a hot interstellar medium. This implies that the galaxies have a) a low supernova rate; b) high total gravitational binding masses and c) continuous star formation. Much of the gas in isolated galaxies is probably due to stellar mass-loss. The details of its behaviour are complex.

1. INTRODUCTION

Diffuse X-ray emission from individual elliptical galaxies in the Virgo cluster was discovered with the Einstein Observatory by Forman et al. (1979). Widespread X-ray emission due to intracluster gas was already well-known, but except for peaks on central galaxies such as M87 and NGC 1275, individual galaxies had not been previously detected. A 'plume' of emission from the fast-moving galaxy M86 (Forman et al. 1979), a diffuse component to Cen A (Feigelson et al. 1982) and studies of the X-ray spectrum (Forman, Jones & Tucker 1985; Trinchieri, Fabbiano & Canizares 1985; hereafter FJT and TFC, respectively) combine to make thermal emission (bremsstrahlung, line and recombination radiation) from hot gas at a temperature $\sim 10^7$K the most plausible origin for the X-rays. Low-mass X-ray binaries, such as found in the bulge of our Galaxy and in M31, are only expected to make a significant contribution in low luminosity ellipticals (FJT; Trinchieri & Fabbiano 1985).

Long & Van Speybroeck (1983) and Biermann & Kronberg (1983) showed that a wide range of nearby E and S0 galaxies are X-ray emitters and Nulsen, Stewart & Fabian (1984; hereafter NSF) found X-rays from a relatively isolated elliptical galaxy, NGC 1395. The X-ray emission is an intrinsic property of early-type galaxies and is not directly related to the environment. FJT carried out the first comprehensive X-ray study of a moderately large number (55) early-type galaxies and presented surface brightness profiles, X-ray spectra and mass estimates. These estimates were high enough to confirm that many E and S0 galaxies have dark haloes.

The work of FJT and the statistical analysis by Trinchieri &

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Fabbiano (1985) showed that the X-ray luminosity, L_X, correlates with the visual luminosity, L_V, so that

$$L_X \propto L_V^a \tag{1}$$

with $1.5 \lesssim a \lesssim 2$. This relation is explained by cooling of stellar mass loss and gravitational heating (NSF; TFC; Sarazin 1986; Canizares, Trinchieri & Fabbiano 1986, hereafter CTF). Further detailed studies have been carried out by TFC, CTF and Stanger & Warwick (1986). All of the data are from the Einstein Observatory in the energy band ∿ 0.2 to 4 keV and, apart from a few exceptions (e.g. Mason & Rosen 1985), no useful X-ray observations of individual early-type galaxies have been carried out since it became inoperational. Further X-ray observations must await the launch of ROSAT and of AXAF.

The mass of X-ray emitting gas in a typical E or S0 galaxy is between 10^9 and $10^{10} M_\odot$ and at a temperature of ∿ 10^7K. This is consistent with accumulated stellar mass-loss heated by collisions and gravity. Given the simplicity of this picture, it is worth re-examining previous widely-held views that early-type galaxies are devoid of gas. Although some do contain significant quantities of HI and patches of star formation, this does not provide a general explanation for the removal of stellar mass loss. The main argument used by Faber & Gallagher (1976) against the retention of hot gas was that the gas is not observed optically (by Hβ emission, for example). We now know that the central gas density is much lower than they assumed. They concluded either that galactic winds powered by Type I supernovae sweep out the gas (Mathews & Baker 1971) or that star formation with a preference for low-mass stars operates. Although this last option was considered favourably by Jura (1977) and now appears to be correct, galactic winds were preferred and featured in many later discussions (e.g. MacDonald & Bailey 1981; White & Chevalier 1983; but see Norman & Silk 1979 for another view). In fact, the presence of detectable X-ray emission from E and S0 galaxies means that galactic winds are rare or even non-existent at the present time (see Mathews & Loewenstein 1986 for a discussion of the evolution of galactic winds). The mass-loss rate would otherwise far exceed the integrated stellar mass-loss rate (NSF). Consequently the supernova rate in early-type galaxies must be much lower than previously estimated (NSF; White & Chevalier 1984; Canizares 1986; Sarazin 1986; Thomas 1986). (Preliminary results of a large optical supernova search by Tammann and collaborators (private communication) indicate this is indeed the case and the rate is less than $(500\ \mathrm{yr})^{-1}$). Furthermore, the relatively short cooling time of the hot gas means that star formation is widespread in early-type galaxies.

In summary, the X-ray observations show that the mass of gas and star formation rate of E and S0 galaxies are not very different from those in spiral galaxies. The distribution of the hot gas can, in principle, provide accurate mass profiles and limits on total masses. In the next Section we argue that the total masses are large and that early-type galaxies possess massive dark haloes. Estimates of the rate at which gas is cooling throughout the galaxies and the consequent star formation and optical emission are then discussed. It appears that the gas contains a range of densities throughout and its flow is complicated. The much larger (10 - 1000 $M_\odot yr^{-1}$) cooling flows that are observed around many dominant central cluster galaxies are discussed only briefly; more detailed reviews are given by Fabian, Nulsen & Canizares (1984) and Sarazin (1986). Finally, some obvious implications for nucleus activity, jet propagation, cold discs etc. are outlined. It is clear to us that X-ray data are essential ingredients for a complete understanding of early-type galaxies.

2. GRAVITATIONAL MASSES

Large velocity flows approaching sonic speeds imply impossibly large mass rates in X-ray luminous galaxies (NSF) so it is safe to assume that hydrostatic equilibrium is a good approximation.

$$\frac{dP_{gas}}{dr} = - \rho_{gas} \frac{d\phi}{dr} \tag{2}$$

P_{gas}, ρ_{gas} and ϕ are the gas pressure and density and the gravitational potential, respectively. This can be rearranged, for an ideal gas, to give (Fabricant, Lecar & Gorenstein 1980);

$$\frac{d\phi}{dr} = - \left(\frac{kT}{\mu m}\right) \left(\frac{d \ln \rho_{gas}}{dr} + \frac{d \ln T_{gas}}{dr}\right) \tag{3}$$

The gravitational potential, and thus mass profiles can then be measured from observations of the gas density and temperature profiles. As the X-ray emission varies as ρ^2_{gas}, the density is usually well-determined, but the temperature is much less so. Where measured, T appears to increase outward (Forman, Jones & Tucker 1985). Estimates of the gravitational mass profiles of the best-studied galaxies are given by FJT, TFC, Thomas (1986), Canizares (1986) and Sarazin (these proceedings). There are uncertainties but it appears that many E and S0 galaxies have masses within $\sim$ 50 kpc that exceed $10^{12} M_\odot$. NGC 4472 (M49) appears to have a massive dark halo with a core radius of 10 - 60 kpc and a total mass profile similar to its neighbour NGC 4486 (M87; Thomas 1986).

A minimum lower limit to the total gravitational mass of a galaxy is obtained by assuming that the observed hot gas, of temperature T and pressure P_o at radius r_o, is confined by a convectively stable outer atmosphere through which the pressure decreases out to P_∞ at r_∞ (Fabian et al. 1986). The whole atmosphere sits at rest in the potential well of the galaxy. The total gravitational binding mass is minimised by the atmosphere with the steepest falling temperature gradient and, for convective stability, this follows an adiabat. The minimum total mass, M_T, is given by

$$M_T \geqslant \frac{5}{2} \frac{kT\, r_o}{G\mu m} \frac{[1 - (P_\infty/P_o)^{2/5}]}{(1 - r_o/r_\infty)} \tag{4}$$

(Fabian et al. 1986). When applied to the galaxies well-studied by FJT and TFC, $\langle M \rangle > 5 \times 10^{12} M_\odot$ and $\langle M_T/L \rangle > 75$. Elliptical and S0 galaxies must have massive dark haloes in order to confine the observed X-ray gas.

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We have assumed that $P_\infty << P_\sigma$, which is reasonable anywhere but near the centre of a cluster. The gas temperature is the most uncertain quantity. Measured values are an average and need not apply at r_o. However, the shape of the X-ray surface brightness profiles means that about half the flux originates from within $r_o/4$. A lowest limit is then obtained by dividing our straightforward limits by 4. The mean total mass-to-light ratio is now comparable with that for spiral galaxies, so we can definitely conclude that E and S0 galaxies have dark haloes at least as important as those of spirals. This lowest limit is very conservative and runs into some problems with interpretation due to the low temperature of the outer gas near r_o. The density and mass of gas necessary to produce the observed flux is then increased substantially, as is the cooling rate to many solar masses per year. The straightforward estimate (Eqn.4) is probably more realistic.

Our mass limit was obtained by assuming that all the mass lies within r_o. This leads to a contradiction between M_T and other estimates of $M(< r_o)$ in many cases. This is acceptable since the confining mass will be distributed over a region much larger than r_o. Whilst that has the effect of reducing $M(< r_o)$, it also increases M_T. An isothermal halo ($M(< r) \propto r$) typically requires that M_T is 3 times greater than our limit. Overall, the X-ray emission from E and S0 galaxies strongly suggests that their total masses exceed $10^{13} M_\odot$ and total mass-to-light ratios are some hundreds.

3. DENSITY PROFILES AND MASS DEPOSITION RATES

The radiative cooling time of most hot gas in ellipticals is shorter than a Hubble time. In the absence of a heat source, the gas cools and forms stars, settling inward and forming a cooling flow (NSF; Stanger & Warwick 1986; Thomas 1986; CFT). Even if there is some heating, such as from supernovae, it is not clear that the gas is prevented from being thermally unstable, as the densest gas will continue to cool.

The mass deposition rates of cooled gas in 18 E and S0 galaxies and the bulge of the Sombrero galaxy have been estimated by Thomas *et al.* (1986). The X-ray images are deprojected by dividing the counts into annular rings about the galaxy centre and then estimating count emissivities in concentric shells. These are related to density and temperature through the emission and detection processes. The optically measured velocity dispersion gives ϕ for the equation of hydrostatic support which further relates particle density, n, and T and enables n(r) and T(r) to be determined separately. Estimates of n(r) are particularly robust (Fig. 1), whereas T(r) depends sensitively on $\phi(r)$ and the value of pressure at one radius, typically the outer radius. We choose this pressure so that the overall spectrum from the gas is consistent with gas at 1.5×10^7K.

As a first method (a) for estimating the mass deposition profile assume that no radial flows occur and all gas injected into a shell cools there. The mass deposition rate in that shell is given by

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$$\Delta \dot{M}_a = \frac{\Delta L}{H}, \tag{5}$$

where ΔL is the X-ray luminosity of that shell and H is the enthalpy of the gas ($5/2\ kT/\mu m$). $\dot{M}_a(<r)$ is then obtained as $\Sigma \Delta \dot{M}_a$.

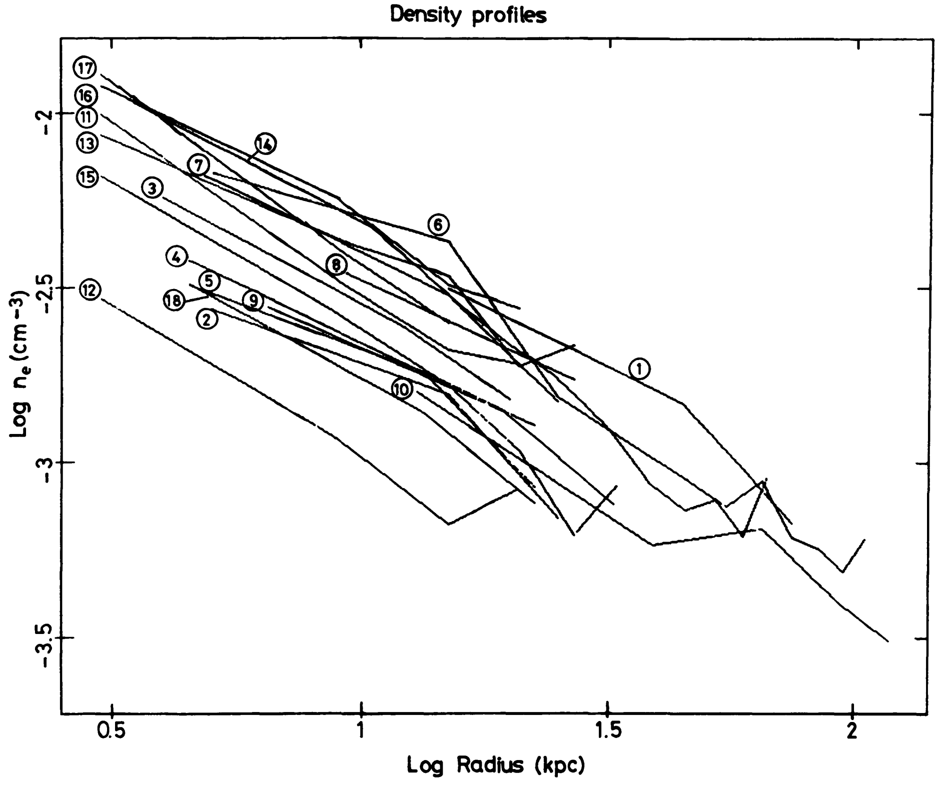

Figure 1. Electron density profiles of the hot gas in a sample of 18 E and S galaxies and the Sombrero galaxy. The individual galaxies are identified in Table 1 of Thomas et al. (1986).

A second method (b) allows radial flows with 2 gas phases. One phase flows across a shell whilst the other cools out there. There is no mass injection and

$$\dot{M}_b = \frac{\Delta L - \dot{M}\ (\Delta H + \Delta \phi)}{H} \tag{6}$$

The term $\dot{M}\ (\Delta H + \Delta \phi)$ represents energy losses or gains by the gas flowing across the shell.

Finally, (c), we allow radial flows with 2 phases and mass ($\Delta \dot{M}_+$) and energy (H_+) injection.

$$\Delta\dot{M}_c = \frac{\Delta L + \dot{M}\,(\Delta H + \Delta\phi) - \Delta\dot{M}_+\,(H_\mp - H)}{H} \qquad (7)$$

Both inflow and outflow are possible.

The first 2 methods run into significant problems. Estimating $\dot{M}_+$ at $1.5 \times 10^{-11} M_\odot yr^{-1} L_{\odot B}^{-1}$ (Faber & Gallagher 1976), we find $\dot{M}(< r_{cool}) << \dot{M}_+(r_{cool})$. In particular, we expected that $\dot{M}(r_e) = \dot{M}_+(r_e)$ but the discrepancy is even worse there (Fig. 2). In other words, the rate of mass deposition is much less than the expected rate of mass injection. There are ways of overcoming this problem. The stellar mass loss rate may not mix into the hot phase, so is not detected in X-rays (see White & Chevalier 1983 and Thomas 1986). A study of the evolution of red giant ejecta suggests that this is indeed likely and $\dot{M}$ estimated from X-rays is then a lower limit on the total $\dot{M}$. Alternatively, the rate of stellar mass loss may be overestimated. The mass of the resulting white dwarf is basic to global estimates of the mass loss from a red giant.

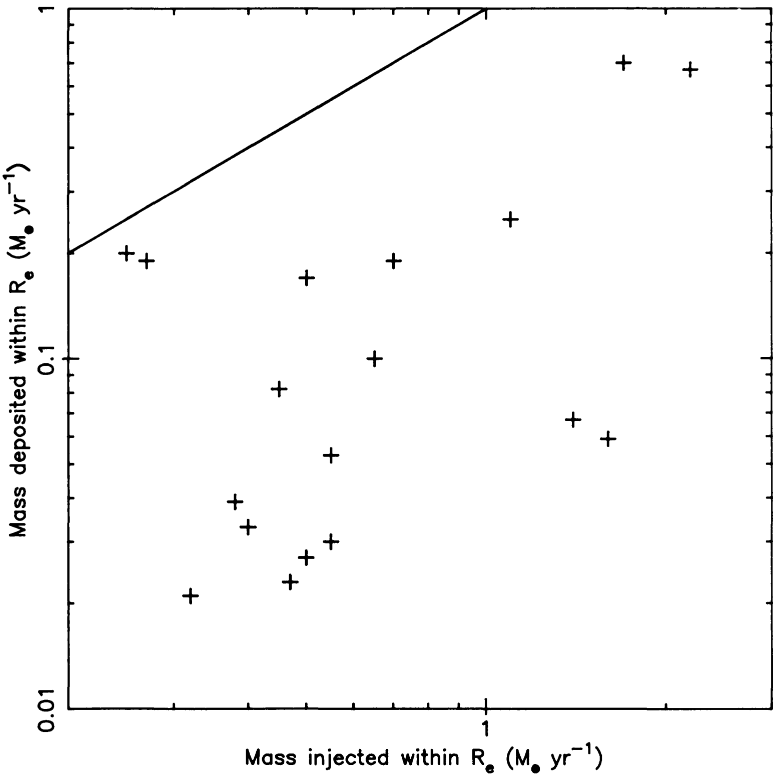

Figure 2. Mass deposited within the effective radius, $\dot{M}_a(r_e)$, in the 18 galaxies shown in Fig. 1, compared with the expected mass injection, $\dot{M}_+(r_e)$. Most of the points fall well below the solid line representing $\dot{M}_a(r_e) = \dot{M}_+(r_e)$.

Could white dwarfs in E and S0 galaxies be more massive ($\gtrsim 0.9\ M_\odot$) than those ($0.6 - 0.7\ M_\odot$) than those in our Galaxy? Lastly, significant photoelectric absorption due to cooled gas (column densities $\gtrsim 10^{21} cm^{-2}$) could mean that we underestimate the X-ray luminosity and thus mass deposition rate. Coupled with a lower gas temperature we could perhaps force $\dot{M}_a(< r_e)$ to equal $\dot{M}_+(< r_e)$. Such column densities correspond to HI masses $\sim 10^8 M_\odot$ within r_e and are consistent with X-ray spectra (TFC).

Our last method can accommodate all these problems by allowing the inner gas to flow out a little way whilst the outer gas flows in. This is possible with multiphase gas provided that there is some heat source consistent with a low supernova rate. The system then resembles a complex galactic fountain, as discussed for our galaxy by Bregman (1980) and others. Gas at large galactic radii may have accumulated from earlier times when the galaxy was more active (Mathews & Loewenstein 1986).

In summary, we find that the hot gas in ellipticals is continually cooling at total rates of at least 0.02 to about $3\ M_\odot yr^{-1}$. The higher rates are associated with central galaxies in groups such as NGC 4472 in Virgo and NGC 1399 in Fornax. There is then gas at all temperatures from $\sim 1 - 2 \times 10^7$K down to 100 K and below. Much of the stellar mass loss is probably not shocked to the higher temperatures and is not heated much beyond 10^4K. Measurements and limits on HI in E and S0 galaxies suggest that most of the cooled gas rapidly and efficiently forms stars.

Much larger mass deposition rates of between 10 - 1000 $M_\odot yr^{-1}$ are inferred in 30 - 50 percent of the clusters studied with the Einstein Observatory (Stewart et al. 1984). The cooled gas is deposited such that $\dot{M}(< r) \propto r$ over a range of radii in the central galaxy out to 100 - 200 kpc (see Fabian, Arnaud & Thomas 1986).

4. STAR FORMATION AND OPTICAL LINE EMISSION

The evidence collected so far indicates that gas is continually cooling throughout normal and S0 galaxies. Unless estimates of stellar mass loss are grossly incorrect, the total mass deposition rate from all gas is $\sim 1\ M_\odot yr^{-1}$. The star formation rate then approaches that for spiral galaxies (see e.g. Kennicutt 1983). Some fraction of the cooled gas probably forms stars with a 'normal' initial-mass-function (IMF) but the remainder could become 'dark' matter ('Jupiters' or whatever). As pointed out by Jura (1977), the pressure of any interstellar medium in ellipticals is high and this could depress the Jeans mass and skew the IMF to low masses. There will be little dust in the X-ray emitting phase due to sputtering (see Draine & Salpeter 1979). Cold blobs of gas from the mass loss of individual stars probably contain less than $1\ M_\odot$ and so cannot collapse to form OB stars unless there is considerable coalescence of blobs.

Some fraction of the cooled gas may accumulate as larger clouds in the galaxy core in some ordered form, particularly as a disk where relative velocities can be much less. Dust injected into cooled gas is not sputtered and so the hot phase spread throughout the galaxies is not inconsistent with a small dusty region in the core. Optical emission lines should occur from any region where massive stars form and (much weaker) from the cooling gas. There is, of course growing evidence that emission lines are common (Caldwell 1984; DeMoulin-Ulrich, Butcher & Boksenberg 1984; Phillips et al. 1986; Sadler these Proceedings).

Widespread cooled gas provides a ready explanation for observations of star formation in elliptical galaxies (Bertola et al. 1980; Gunn, Stryker & Tinsley 1982; Rose 1984; Pickles 1985 and these Proceedings; Veron & Veron 1986). The cycling of stellar mass-loss will cause chemical evolution of the stellar population and create colour gradients. The current rarity of supernovae in ellipticals discussed earlier means that the elements synthesised and ejected by giants will build up relative to iron.

Cooling flows are a large internal source of gas in elliptical galaxies. Mergers and other external causes need not always be invoked to explain observational phenomena. This is particularly relevant to the extensive optical line emission commonly observed in the central galaxy of cluster (and group) cooling flows (Kent & Sargent 1979; Ford & Butcher 1979; Heckman 1980; Fabian et al. 1982; Cowie et al. 1983; Hu, Cowie & Wang 1985). Johnstone, Fabian & Nulsen (1986) have found in such galaxies that the $H\beta$ luminosity correlates inversely with the strength of the 4000 A break in the underlying stellar population. This shows that most of the line emission is due to photoionization by the radiation from massive stars and cooling gas. A small fraction (1 - 10 percent) of the mass deposited forms stars with a 'normal' IMF, the hotter members of which produce ionizing radiation and fill in the 4000 Å break. This fraction may be associated with the largest cooling blobs in the flow. Only 0.5 to 10 $M_\odot yr^{-1}$ of 'normal' star formation is then occurring in most dominant galaxies (see also Bertola et al. 1986 and O'Connell, these Proceedings), but the rate is 100 $M_\odot yr^{-1}$ in the most extreme case, PKS 0745-191. The remainder of the deposited matter presumably forms 'dark matter' (Fabian, Arnaud & Thomas 1986).

5. ACTIVITY, JETS AND SHELLS

A general interstellar medium has obvious consequences for central activity. Only a small fraction of the cooling flow need penetrate to a central mass to power a luminous active nucleus by accretion. The hot medium is pervasive and, if Bondi accretion takes place, the accretion radius adjusts such that $\dot{M} \approx (1 - 10)$ percent of $\dot{M}_{Edd}$ (Begelman 1986; NSF). Radio jets emerging from the nucleus are shaped by the surrounding interstellar medium (Sanders 1983).

A sudden global perturbation of the gas in an E or S0 galaxy, perhaps due to a nuclear outburst or a merger, could cause the star formation rate to increase briefly. Stars formed from matter that was in a highly subsonic flow are 'cold' in the sense of low velocity dispersion and will undergo phase-wrapping (Quinn 1984) and give rise to Malin-Carter (1980) shells. Cooled gas is a ready and widespread internal source of 'cold' stars.

6. THE EVOLUTION OF E AND SO GALAXIES

Substantial amounts of hot gas are an intrinsic part of all elliptical and SO galaxies. Only those galaxies which are kept fully-stripped in rich clusters are likely to be devoid of their own gas and even there the intracluster gas is present. The pressure of the gas is much higher than in spiral galaxies; nT is $\sim 10^5 - 10^6$ cm^{-3}K. The presence of hot gas in individual galaxies means that their total gravitational binding masses are large. Much of the gas is cooling, at rates of between 0.02 and 1000 $M_\odot yr^{-1}$, depending upon whether the galaxy is a small elliptical or a dominant cluster galaxy. Mass deposition from cooled gas is widely spread throughout the galaxies and 1 to 10 per cent of this gas form stars with a 'normal' IMF. Continuous star formation is thus important when modelling the evolution of early-type galaxies and in particular central cluster galaxies.

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DISCUSSION

Ebneter: You listed a number of active galaxies which contain cooling flows. All of these galaxies are dusty ellipticals (and an additional one is NGC 708, by the way). Do you think that the dust is being formed in the cooling flow?

Fabian: No. The dust is perhaps associated with stellar mass loss that was never heated to X-ray temperatures.

Ebneter: If the dust and gas *are* coming from the evolved stars in the galaxy, how does it end up in a nice, rotating disk of gas? All of the galaxies listed have very nice, regular dust lanes and rotating gas disks.

Fabian: I don't know, but the mass of the gas in disks is much smaller than the total stellar mass loss in those galaxies. Consequently, the small gas fraction that cools and has the angular momentum of stable orbits may remain there.

Sadler: Frogel and Whitford have recently used strong–lined M giants in the Galactic bulge to synthesize the IR stellar population in ellipticals. They derive a mass injection rate about a factor of ten *lower* than the Faber and Gallagher value.

Toomre: Did I hear you right in still entertaining the notion that the Malin/Quinn–like shells could possibly be features that somehow form spontaneously (or even otherwise!) in the *very hot* gaseous X–ray halos which certainly exist in, or surround, many of the ellipticals? Whatever gas–dynamical process do you feel could possibly give rise to such sharp–edged features in those hot gaseous spheres?

Fabian: Distributed star formation occurs in ellipticals from the hot gas. These stars are cold and could 'phase–wrap' as in Quinn's—and your—models.

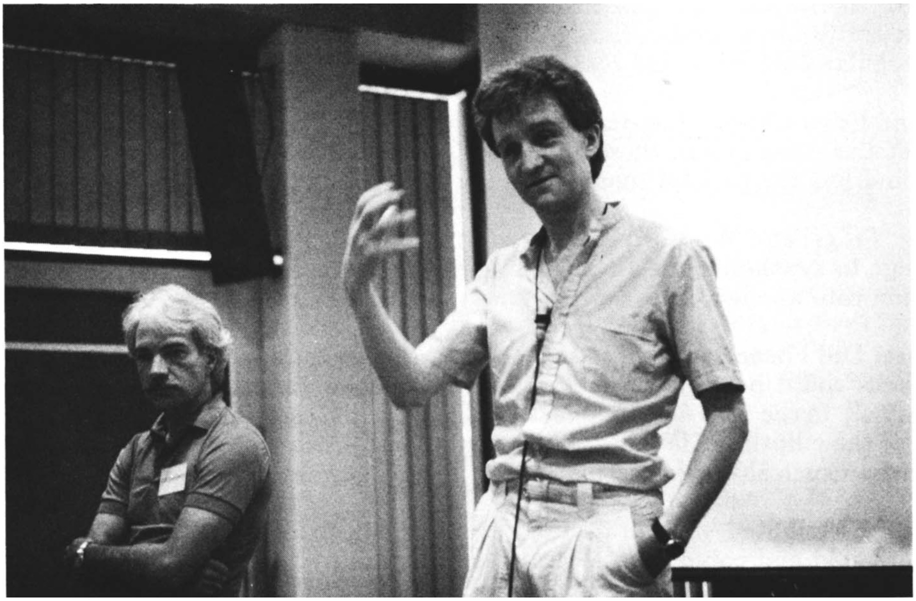
King: It would be interesting to have comparable X–ray observations in the Coma cluster, where there would be a real confrontation. In Coma, dynamical–friction arguments set an *upper* limit to M/L that is considerably lower than the *lower* limit that you find.

Fabian: Presumably most of the mass that we infer to be present in elliptical galaxies is at large radii (hundreds of kpc). In a cluster such as Coma, these halves will overlap and I assume that they merge to form the general cluster potential.

Lauer: Looking at your list of lower limits to galaxy masses I noticed that isolated faint galaxies had the highest limits, while several bright ellipticals including those in Virgo had much more modest lower limits. Have you looked at M/L as $f(L)$ or as function of isolation?

Fabian: No, but I will do. I think that your comment strengthens our conclusion that the mass is associated with the ellipticals.

Binney: I think Cowie and his collaborators looked for a velocity gradient in the $H\alpha$ filament around NGC 1275 and found nothing significant. I recall reassuring myself that if the rotation parameter of the entire cluster has the canonical value $\lambda = 0.07$ (Efstathiou and Jones, 1979, *Mon. Not. R. astr. Soc.*, **186**, 133), and the gas in Perseus has lost from the cluster center a mass equal to the conventional ($M \leq 10^{12} M_\odot$) mass of of NGC 1275, then the present rate of rotation of the cluster gas could not have been detected by Cowie *et al.*



Fabian fielding questions. Canizares looks on.

The audience listens attentively.

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