COOLING FLOWS AND THE FORMATION OF DARK MATTER

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ABSTRACT. The distribution of matter condensing out of cooling flows in clusters of galaxies and individual elliptical galaxies has been studied using X-ray data and is found to resemble the expected mass profiles of the underlying galaxies. Most of the cooled gas must create objects of high mass-to-light ratio, although some more normal stars are produced. Cooling flows provide an observable mechanism for the continual formation of dark matter around galaxies. Since the conditions at galaxy formation are similar to those in cooling flows if the gas reaches the virial temperature, we suggest that they are local models of galaxy formation.

1. INTRODUCTION

The evidence for cooling flows in clusters of galaxies has been reviewed at this symposium by Canizares (1986) and Sarazin (1986) and elsewhere by Fabian, Nulsen & Canizares (1984) and Sarazin (1985). Briefly, the process involves the cooling of hot gas in the cores of clusters and galaxies by X-ray emission. The cooling gas is pushed inward by the pressure of outer, less dense, gas. Thermal instability causes small density perturbations to grow and drop out of the flow over a wide range of radii within the cooling region. Some of the blobs are visible through optical line radiation. Here we discuss new results on cooling flows in individual elliptical galaxies and on the variation of mass flow rate with radius in galaxies and in central cluster galaxies. There are strong indications that the envelopes of the central galaxies are still being formed at the present epoch by this processs and that much of the cooled gas condenses into objects of high mass to (visible) light ratio. At least some 'dark matter' is baryonic. The profile of mass deposition in a cooling flow resembles that of the mass profile of the underlying galaxy.

The nature of the condensed objects remains a problem, (as does that of most dark matter). There is clear evidence that a solar neighbourhood initial-mass-function is **not** involved. What we do infer from the X-ray and other data of the large flows is that matter

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condenses from hot gas at a rate and in a manner that builds a large extended galaxy. Some stars of solar mass and more are also formed. Cooling flows may be a model for the formation of galaxies. Distant cooling flows ($z \sim 1$) are probably already observed around some of the 3C radio galaxies.

2. INTERPRETATION OF THE X-RAY DATA

Imaging and spectroscopic X-ray data, primarily from the Einstein Observatory, are the major source of information on cooling flows. We have made extensive use of the X-ray surface brightness profiles from the Imaging Proportional Counter (IPC) and High Resolution Imager (HRI); much of these data are discussed by Jones & Forman (1984). In order to obtain gas density and temperature profiles, we have employed three separate methods.

2.1. Deprojection of surface brightness profiles:

The X-ray surface brightness from most circularly symmetric clusters rises so steeply that a direct deprojection of the counts gives a stable solution (Fabian et al. 1981). X-ray counts accumulated in concentric annular bins are thereby converted into count emissivities, ε, in nested shells at the cluster. The cluster is assumed to be spherically symmetric. (Small departures from symmetry are not important, Fabian et al. 1981). ε is related to the gas density and temperature, n and T, through the emission process (thermal bremsstrahlung and line emission), the detector response and the intervening photoelectric absorption, i.e. $\varepsilon = f(n, T)$ where f is a known , but complicated function. We can then separate n and T with the equation of hydrostatic equilibrium,

$$\frac{dP}{dr} = - \rho \frac{d\phi}{dr}$$

where P and ρ are the gas pressure and mass density and ϕ is the gravitational potential. This potential is estimated from an assumed mass profile (say, a King law) and galaxy velocity dispersion, both obtained from optical data. Gas density profiles are thereby obtained which, due to the limited response of the detectors to temperature variations, are consistent and accurate to about 10 percent. The temperature profiles are much less certain since they depend strongly on ϕ. Some limits can be placed by ensuring that the re-projected solution does not conflict with the overall spectrum of the cluster or any spectroscopic components (e.g. lower temperatures or lines, see e.g. Mushotzky et al. 1981; Canizares 1981). Where there are strong constraints on the temperature profile, we can of course determine ϕ directly from the X-ray data (Fabricant & Gorenstein 1983; Stewart et al. 1984a).

Where the radiative cooling time of the gas is less than the Hubble time we can solve for the rate at which matter is cooling out of the flow at each radius, $\delta\dot{M}$, from the local luminosity,

$$\delta L = \dot{M}\left(\frac{5}{2}\frac{k\Delta T}{\mu m_H} + \Delta\phi\right) + \delta\dot{M}\left(\frac{5}{2}\frac{kT}{\mu m_H} + f\Delta\phi\right)$$

where $\dot{M}$ is the rate at which matter flows completely through that annulus and f is a weighting factor ($\sim$0.5) for the gravitational work done on $\delta\dot{M}$ (see Fabian et al. 1985a). $\dot{M}$ is found to increase with radius to substantial rates (20 $M_\odot yr^{-1}$ in M87, Stewart et al. 1984a; 300 $M_\odot yr^{-1}$ in NGC 1275, Fabian, Nulsen & Canizares 1984). A selection of results for $\dot{M}(r)$ is shown in Fig. 1.

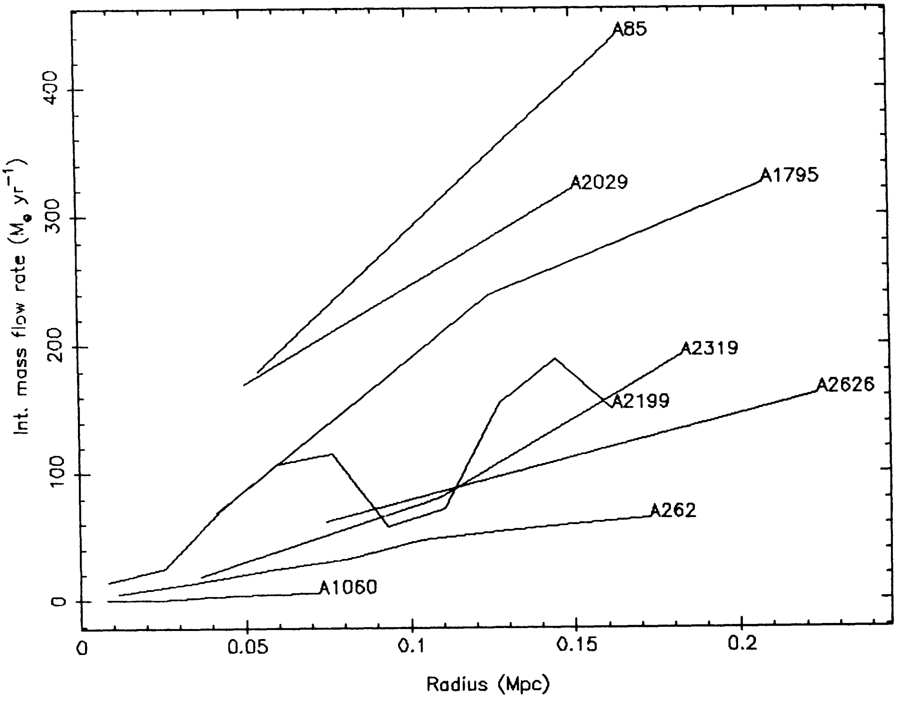

Fig. 1. Integrated mass flow rates, $\dot{M}$, in a number of cooling flow clusters. They increase in a similar manner, although there is a wide spread in the distances and in the quality of the data.

2.2. Model fitting:

The equations of continuity, force and energy for gas in a spherical potential can be directly integrated to obtain surface brightness profiles which can then be compared with the data (Fabian et al 1981; Thomas et al. 1985). Once again, ϕ is estimated from optical work. As discussed above, the X-ray data definitely require that $\dot{M}$ is not constant, and some theoretical prejudice must then go into the selection of the form of its radial dependence. In this respect, the deprojection method is much simpler and freer from pre-conceived ideas.

The results for detailed fits to the X-ray profile of the Virgo elliptical galaxy, NGC 4472 (Thomas et al. 1985) are shown in fig. 2. In this case we include the possibility of distributed mass and energy sources (from stellar mass loss and supernovae) as well as sinks for cooled matter. The profile beyond ∿ 20 kpc requires a dark halo, as reported by Forman, Jones & Tucker (1985). Cooling is important within ∿ 60 kpc and the data require that the matter drops out of the flow in a distributed manner since the gravitational energy liberated in falling to the luminous core radius is too large. The X-ray emission cannot be explained by any near- or super-sonic flow such as would be expected if a wind were operating. The inflow velocities are highly subsonic (1 - 10 km s^{-1}) and the mass flow rate falls steadily inward from ∿ 0.8 $M_\odot yr^{-1}$ at 60 kpc (fig. 3).

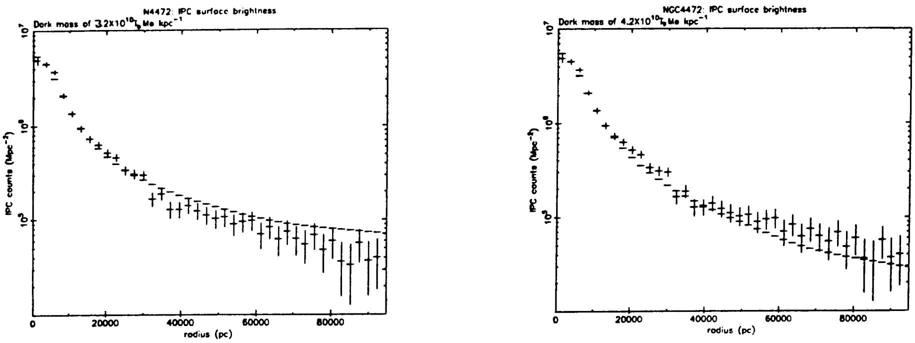

Fig. 2. Comparisons of the IPC surface brightness profile of NGC 4472, at a distance of 15 Mpc, (crosses) with the results of a detailed cooling flow model including an isothermal dark halo of core radius 10 kpc and the spatial response of the detector. The total dark mass out to 100 kpc is 3.2 x $10^{12} T_7 M_\odot$ (left-hand panel) and 4.2 x $10^{12} T_7 M_\odot$ (right-hand panel), where the outer gas temperature is $10^7 T_7$ K. The influence of the dark mass is seen even at 20 kpc. Further systematic uncertainties in the data beyond ∿ 50 kpc due to background subtraction and departures from spherical symmetry are not included.

The heating rate due to supernovae, assumed by White & Chevalier (1983) in a study of flows in elliptical galaxies to be that due to ∿ 1 event per 30 y, must be reduced to ∿ 1 per 100 y. Also it seems that some of the stellar mass loss - red giant winds and planetaries - condenses back into stars, or low-mass objects before it has a chance to shock on other cold gas (see also White & Chevalier 1983).

The X-ray data are clearly opening a new era in the study of gas in galaxies. The amount of gas and star formation in a large elliptical galaxy is only a little less than that in a spiral galaxy such as our own.

2.3. Comoving inflow of cooling blobs:

The necessity that matter drops out of the flow at all radii suggests to us and Paul Nulsen that the gas within a cooling flow consists of many phases which are intimately mixed. To make any progress, we assume that these phases are comoving, as expected for small blobs at X-ray emitting temperatures (Cowie, Fabian & Nulsen 1981). It is possible that the hottest phase does not comove and it may even flow outward (Nulsen, private communication).

Beyond the outermost radius where the cooling time equals the age of the cluster atmosphere we assume that there is a small range of density variation. At smaller radii, they develop according to the thermal instability. The cooling gas is pushed subsonically inward by the pressure of the outer gas and the initially densest blobs cool first and drop out from the flow at the largest radii. The remaining gas flows further inward with blobs of decreasing initial density finally cooling and collapsing. We can solve for this process using a modification of the deprojection method where there are as many phases as annular bins and we (numerically) follow each phase outward from the centre. The count emissivities are now expressed as $\varepsilon(n_1, n_2, T_1, T_2)$ as the gas cools from n_1, T_1 to n_2, T_2, over an annulus. To obtain this function we have integrated the spectra from Raymond & Smith (1977), folding in the detector response and absorption as before.

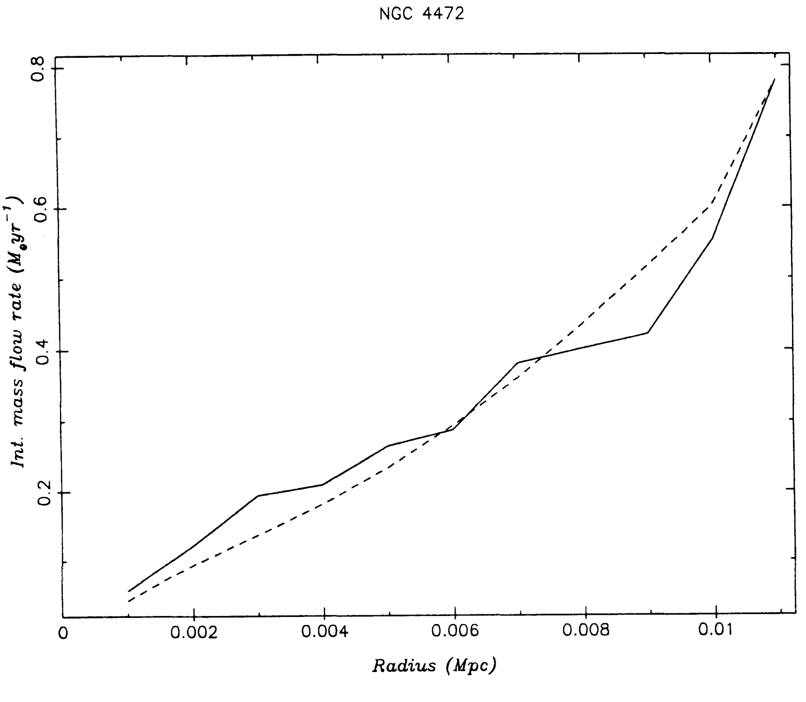

Fig. 3. The integral mass flow rate within NGC 4472 from the deprojection method (solid line). The model fit (not shown) is in good agreement. The dashed line indicates the gravitational mass profile scaled to the outer radius shown.

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We have applied this method to a few clusters for which there is excellent imaging data (e.g. > 10^5 counts) and find good agreement with the other methods. The results for the region around NGC 1275 in the Perseus cluster are shown in fig. 4. $\delta \dot{M}$ is approximately constant with radius beyond ∿ 20 kpc (there are central-point-source subtraction uncertainties at smaller radii). Matter is dropping out of the flow in a form consistent with the mass profile of a large elliptical galaxy (fig. 5). The total rate of ∿ 300 $M_\odot yr^{-1}$ can supply the total mass of a large central galaxy over a Hubble time.

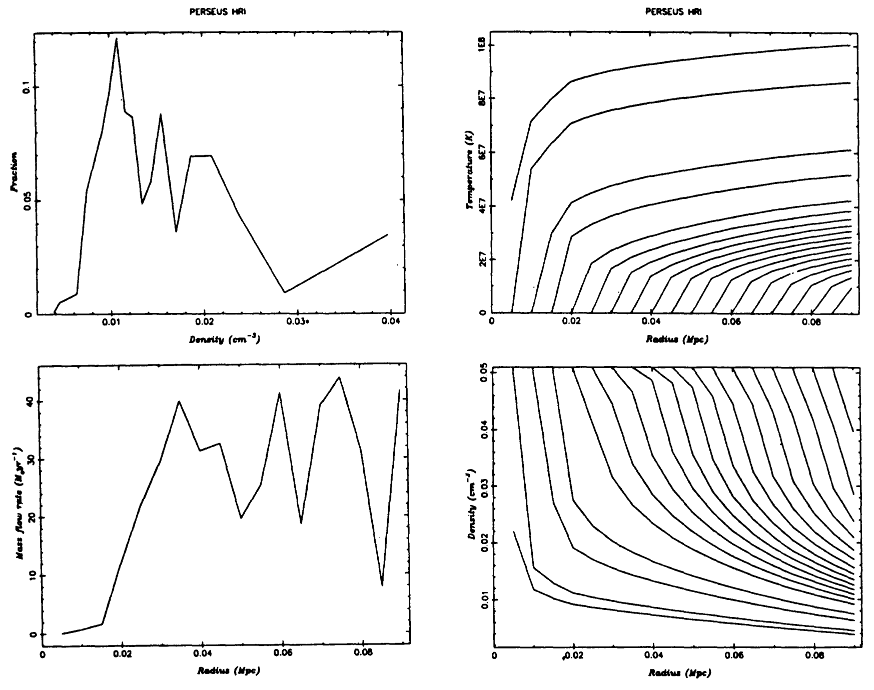

Fig. 4. Results from a multiphase analysis of HRI data from the region around NGC 1275. The right-hand panels show temperature and density profiles for each phase. The upper left-hand panel contains the relative distribution of mass flow with density at the outer cooling radius. The lower left-hand panel shows the rate at which mass drops out of the flow at each radius, $\delta \dot{M}$. Note that $\delta \dot{M}$ is almost constant with radius beyond 2 kpc. Other clusters for which there are good data give similar results.

We conclude this section by stressing that cooling is relatively common in rich clusters (Stewart et al. 1984b), poor clusters (Canizares, Stewart & Fabian 1983) and even isolated elliptical galaxies (Nulsen, Stewart & Fabian 1984). In some cases, very large quantities of matter are condensing out, at a rate that can build a complete galaxy over a Hubble time. The mass of the underlying galaxy is compatible with this possibility. However, there is a problem with the light if the initial-mass-function of the condensed objects is similar to that inferred for the stars in our Galaxy.

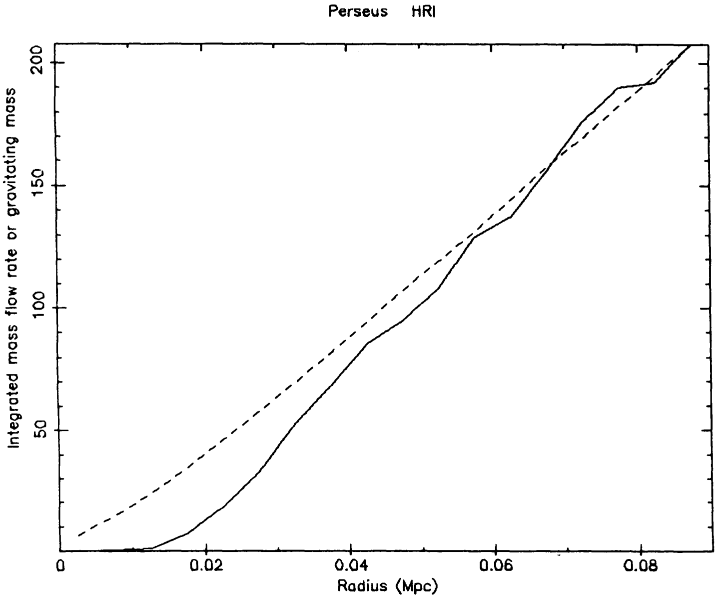

Fig. 5. The integrated mass flow rate, $\dot{M}$, for NGC 1275 (solid line) compared with the assumed mass profile producing $\phi, \rho_* \propto (1 + (r/a)^2)^{-1}$. The mass profile is scaled to agree with $\dot{M}$ at the outer radius. They would agree quantitatively if the dark matter has a velocity dispersion of ~ 240 km s^{-1} and the flow continues for H_o^{-1}.

3. THE FORMATION OF STARS AND CONDENSED OBJECTS IN COOLING FLOWS

The X-ray data on the Perseus cluster around the galaxy NGC 1275 indicate a cooling rate of $\sim$ 300 $M_\odot\,yr^{-1}$ (Fabian et al. 1981). The gas is also observed at $\sim 10^7$K (Mushotzky et al. 1981), by which time it has lost $\sim$ 80 percent of its initial thermal energy (initially, $T \sim 8.10^7$ K), and then as optical and ultraviolet emitting filaments (see Lynds 1970; Kent & Sargent 1979; Cowie et al. 1983 for Hα and Fabian, Nulsen & Arnaud (1984) for Lyα). Absorption by still cooler gas ($T << 10^4$ K) has been detected at 21 cm and a velocity of 5300 km s^{-1} by Crane, van der Hulst & Haschick (1982). We have little doubt that gas is condensing out of the flow. The nature of what it condenses into is highly uncertain.

The implied star formation rate is $\sim$ 100 times that in our galaxy, yet NGC 1275 is not 5 magnitudes brighter than our galaxy. The continuum spectrum of parts of NGC 1275 does resemble that of an A star

(Rubin et al. 1977), so at least some massive stars ($M \gtrsim 3\ M_\odot$) are formed. The IUE data on it show no evidence for an extra-nuclear continuum so we have concluded that less than ∿ 2 percent of the mass flow produces OB stars (Fabian, Nulsen & Arnaud 1984). An uncertainty in this limit due to reddening is eliminated by recent infrared observations of the galaxy at wavelengths of 10 - 400 μm. Gear et al. (1985) show that thermal re-radiation by dust does dominate the spectrum, but can be explained by ∿ 2 percent of the 300 $M_\odot yr^{-1}$ cooling flow producing OB and A stars. This is considerably less than would be expected from a solar-neighbourhood initial-mass-function and, together with the total magnitude limits, requires that the star formation is biased towards low mass stars. The high pressure and lack of dust may be contributing factors (Fabian, Nulsen & Canizares 1982; Sarazin & O'Connell 1983).

Arnaud & Gilmore (1985) have recently observed several central galaxies in cooling flows at the 2.3μm CO feature. This is a sensitive indicator of the relative giant to dwarf ratio of late-type stars. There is no evidence for a dominant population of low-mass dwarfs.

The accumulated mass of condensed matter around NGC 1275 is

$$\dot{M}\, H_o^{-1} = 6 \times 10^{12} \left(\frac{H_o}{50\ \mathrm{km\ s^{-1} Mpc^{-1}}}\right)^{-3} \left(\frac{\dot{M}}{300\ M_\odot y^{-1}}\right) M_\odot$$

comparable to the total expected mass. A simple estimate of the mass-to-(visual) light ratio for the condensed matter is $M/L_V \simeq 10$. For PKS 0745-191 where $\dot{M} \simeq 1000\ M_\odot y^{-1}$, Fabian et al. (1985) obtain $M/L_V > 25$. This is, of course, reduced if the flow has not operated at such a high rate for H_o^{-1} or if $H_o > 50$ km $s^{-1} Mpc^{-1}$ (M/L_V varies as H_o^{-1}) and is increased if some of the observed light is due to a pre-existing galaxy. The A and earlier stars may form within transient low pressure regions in large isochorically cooled blobs . These blobs may also produce most of the observed line emission (Cowie, Fabian & Nulsen 1980). Most of the gas may cool via smaller blobs which emit much less light and form very low-mass stars. (This could accentuate a problem in explaining the high optical line luminosities.) Whether these are nuclear-burning stars, brown dwarfs, Jupiters or even smaller objects is impossible to tell at the present time. Perhaps fragmentation (Low & Lynden-Bell 1976) really works. It does appear that the conditions which produce massive stars may be special to spiral and irregular galaxies (e.g. relatively low pressures, low relative velocities, Giant Molecular Clouds etc.). Cooling flows provide one mechanism for the formation of baryonic 'dark' matter.

4. COOLING FLOWS AT EARLIER EPOCHS AND GALAXY FORMATION

Cooling flows contain both radio-loud (e.g. Cygnus A, $\dot{M} \sim 100\ M_\odot y^{-1}$; Arnaud et al. 1984) and radio-quiet (e.g. AWM 7, $\dot{M} \sim 40\ M_\odot y^{-1}$; Canizares et al. 1983) galaxies. The existence of flows in poor clusters suggests that they are common in sub-clusters, and are subseqeuntly disrupted when they merge to form present-day rich clusters (Stewart et al. 1984b; McGlynn & Fabian 1984). Cooling flows may then be more common in the past. A small fraction of the flow reaching the centre of the galaxy can easily power an active nucleus and so the relatively recent decline of luminous active galaxies, quasars and radio sources may follow the disruption of subclusters. Some traces remain of extended radio sources in the form of wide-angle tails and cluster halo sources (Arnaud et al. 1984).

Although cooling flows with $\dot{M} \gtrsim 100\ M_\odot y^{-1}$ were detectable beyond redshifts of ~ 0.7 by the Einstein Observatory, a more X-ray luminous active nucleus could easily mask its appearance. Consequently, they need not be immediately apparent. The strong optical and ultraviolet emission lines from the cooled filaments and the formation of massive stars are much more readily found out to greater redshifts. The 3CR and other distant galaxies studied by Spinrad & Djorgovski (1984a,b) Butcher & Oemler (1984) and by Lilly & Longair (1984) are good examples (Fabian et al. 1985b). The luminosity of their [OII] emission is similar to that from the $1000\ M_\odot y^{-1}$, $z = 0.1$ cooling flow around PKS 0745-191 (fig. 6; Fabian et al. 1985a). Searches for similar objects which are radio-quiet have not often been carried out, although Hazard & McMahon (private communication) are finding similar spectra on objective-prism Schmidt plates.

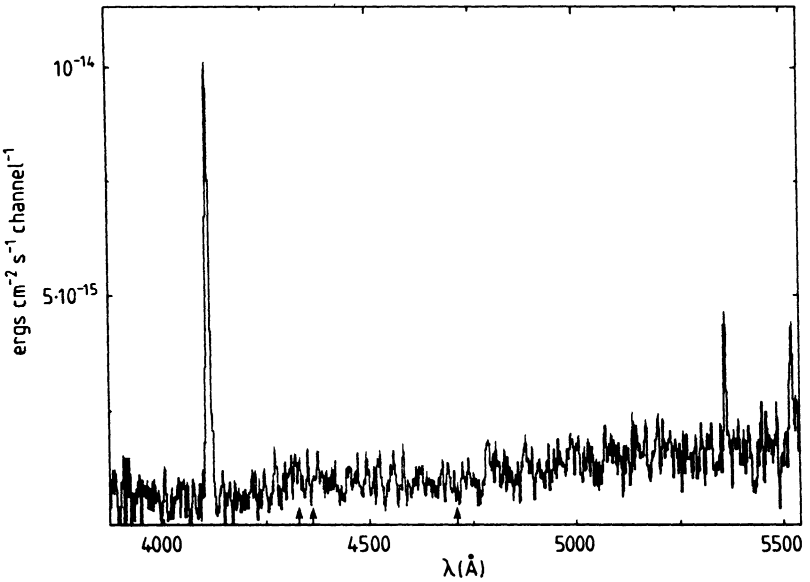

Fig. 6. The strong [OII] line and blue continuum of the $1000\ M_\odot y^{-1}$ cooling flow galaxy, PKS 0745-191 (Fabian et al. 1985a).

The cooled gas probably collapses into sheets which can have a significant covering fraction. Detectable absorption in lines due to CII etc. may then appear in the spectra of background quasars (Crehan private communication).

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In summary, we note that the formation of cold, dark baryonic matter, together with a small fraction of 'ordinary' stars , out of X-ray hot gas is continuing around and within many of the largest galaxies. Some dark matter is then relatively young. If galaxies formed from gas which was heated by collapse to temperatures close to the virial temperature (as suggested by, for example, Rees & Ostriker 1977 and Silk 1977) then the pressure and lack of dust resemble a cooling flow (Fabian et al. 1985b). Only a small fraction of the mass needs to condense into high-mass stars which subsequently explode to seed the rest of the gas with metals. Massive galaxies and their envelopes form over a comparatively long time stretching up to the present epoch, and without many bright stars.

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DISCUSSION

OSTRIKER: This is related to Jim Gunn's question to Sarazin and has to do with the continuity equation. As I understand it, the mass is dropping out of cooling flows in a way that would make mass distributions that are like dark halos, not like visible ellipticals. That is, the mass is making things that are less centrally concentrated than the stars we see now. Then the gas cannot have come out of the stars in the galaxy. Do you agree?

FABIAN: Yes, I agree.

OSTRIKER: So we don't have continual recycling and inflow. Then how did the metals get into the gas? Either they are primordial, or they came out of other galaxies. So either the central galaxy or other galaxies had previously to have had a wind.

FABIAN: It is possible that the initial mass function is pressure-dependent. If so, then low pressures produce high-mass stars. Then to start with you produce lots of high-mass stars, which eject high-metallicity matter into the surrounding envelope. This gas could then make a cooling flow and form the rest of the galaxy. All this requires a wind sufficient to put the metals into the halo. If that wind were very metal-rich, and if there were already some gas at large radii, then the total mass outflow could have been less than the total present mass inflow.

SHAPIRO: In view of the anomalously large number of globular clusters in M87, I'd like to ask whether you can form globulars in these radiative cooling flows?

FABIAN: We have thought about that, and so have Martin Rees and Mike Fall. Conditions in the cooling flows are almost ideal for forming globular clusters. The problem is to keep the gas at 10^4 K long enough to allow it to go Jeans unstable. So maybe the globular clusters in M87 are related to the cooling flow, and maybe they're not.

E. TURNER: If you take seriously the idea that giant ellipticals form continuously, this could have an effect on the Hubble diagram of brightest cluster galaxies. There are at least two possible consequences. First, you might form stars which could become giants in a Hubble time. Second, if you deposit new material within the existing stellar population, you could contract or expand the orbits and therefore affect the number of stars inside some particular observational aperture. In a normal stellar-evolutionary model of elliptical galaxies, luminosity evolution is rapid shortly after the stars form, and then slow thereafter. But your scenario might imply steep luminosity evolution at recent times.

STEIGMAN: Do you require extremely efficient star formation?

FABIAN: 100%.

STEIGMAN: Does that bother you?

FABIAN: Perhaps it should. The big problem is that we see evidence for the gas at 7 keV, 1 keV, in the UV and in the optical. There is evidence for HI absorption in the low-velocity system seen against NGC 1275. But after that, we don't see the gas.

SCHECHTER: Do you expect angular momentum transport in the cooling flow? If not, is the star formation fast enough to keep disks from forming?

FABIAN: This is discussed in a paper by Paul Nulsen. He points out that if the gas is hot, it may be possible for turbulence to transport angular momentum outwards. You could then get HI rings forming in some of these systems.

LARSON: I am very uncomfortable with the suggestion that a hundred $M_{\odot}$ per year, or even a few $M_{\odot}$ per year, could disappear inconspicuously into low-mass stars. Even if nobody understands anything about star formation, there are, after all, a few facts known just from looking up at the sky. One is that we are familiar with star formation in giant molecular clouds. It has been suggested that because the pressure in cooling flows is orders of magnitude higher than that in the interstellar medium in our Galaxy, star formation can be very different. But the pressures in the cores of giant molecular clouds are quite comparable to the pressures in cooling flows. Star formation in the cores of molecular clouds is vigorous and anything but inconspicuous. Massive stars form and large amounts of radiation are produced. I would expect even more extreme things to happen if condensations were to occur in cooling flows. A second fact which has been ignored is that, whenever a mass spectrum has been observed in any kind of stellar system, it has always had a long power-law tail toward high masses which is not too different from Salpeter's original power law. This includes solar neighborhood stars, star clusters in our galaxy, and star clusters in other galaxies. You would require a kind of star formation in which the high-mass tail is completely absent. So the fate of the gas in your cooling flows has little or nothing to do with star formation as we know it.

FABIAN: I agree. We are worrying about all this. It's not just the pressure that is different. If you have shocks, then it is likely that the material is in very thin sheets, and whatever forms at the other end of the shock is sprayed out at shock velocities of hundreds of km s^{-1}. There are many other differences from molecular clouds. For example, there are no molecules, or certainly there are no molecules except H_2 distributed across the face of the cooling flows, because the dust couldn't have survived.

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