Star Formation in Cooling Flows (Invited Paper)

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Abstract: X-ray data show that substantial quantities of hot gas are cooling near the centres of many clusters and groups of galaxies. The existence of such cooling flows has been challenged because of the lack of evidence for star formation from the cooled gas. Spectra of cooling flow galaxies show filling in of the continuum shortward of the break at 4000 Å relative to normal elliptical galaxies. This is consistent with some continuing star formation. Extended regions of line emission are commonly associated with cooling flows. If the initial-mass-function of the newly formed stars which affect the 4000 Å break is like that which applies in the solar neighbourhood, then these stars can also power the line emission. The strength of the 4000 Å break is shown to correlate with the Hβ flux in the manner expected when this is the case. This allows us to estimate the star formation rate from the line luminosity.

The rate of star formation required to account for the line emission still falls well short of the rate at which gas is inferred to be cooling. It is argued that, nevertheless, the cooling gas is probably forming into stars. The overall initial-mass-function must be different from that which applies in the solar neighbourhood, but this should not be surprising given the different ambient conditions in a cooling flow.

Introduction

The presence of substantial quantities of hot gas in clusters of galaxies has been well established from X-ray observations (see review by Sarazin 1986). Indeed, for the richest clusters, the quantity of hot gas is comparable to or greater than the visible mass contained in the cluster galaxies (e.g. Henriksen & Mushotzky 1985).

It has also been known for some time that the radiative cooling time of the gas near to cluster centres is comparable to the Hubble time. Explicitly, with the cooling time defined as

$$t_c = \frac{3p}{2n_e n_H \Lambda(T)} \approx \begin{cases} 
6.8 \times 10^{10} T_7^{4/3} n_{-3}^{-1/3} \text{yr,} & \text{(bremsstrahlung)} \\
3.1 \times 10^{10} T_7^{4/3} n_{-3}^{-1/3} (A/5 \times 10^{-23} \text{erg cm}^3 \text{s}^{-1})^{-1} \text{yr,} 
\end{cases}$$

where the temperature $T = 10^7 T_7 = 10^8 T_8 \text{K}$, the electron density $n_e = 10^3 n_3 = 10^7 n_3 \text{ cm}^{-3}$, $n_H$ is the proton density and $\Lambda$ is the cooling function. Stewart et al. (1984b) found that the cooling time is less than $10^{10} \text{yr}$ near to the centre in about 30 percent of nearby rich clusters of galaxies. In a number of cases the central cooling time is close to $10^9 \text{yr}$, so that it is highly improbable that we are seeing all of these clusters just before the onset of substantial cooling of the gas.

For those clusters where the cooling time of the gas is less than about $10^{10} \text{yr}$ there are two possibilities, either there must be a heat source making up for the radiative loss or the gas must be cooling to low temperatures at present. If the gas is indeed cooling then the timescale for this is long compared to the sound crossing time so that the gas remains close to hydrostatic equilibrium as it cools. The cooling gas is compressed by the surrounding gas resulting in an inflow to the cluster centre where it accretes onto a slowly moving central galaxy if one is present. This type of inflow is known as a cooling flow (see review by Fabian, Nulsen & Canizares 1984).

The inflow is approximately steady within the region where the cooling time is less than about the age of the flow (assumed to be $\sim 10^{10} \text{yr}$). In a steady flow energy conservation requires that the total X-ray luminosity from within a region is just

$$L_X = \dot{M} \left( \frac{5kT}{2\mu m_H} + \Delta \phi \right),$$

where $\dot{M}$ is the rate at which gas flows into the region, $T$ is the temperature of the inflowing gas and $\Delta \phi$ is the change in the gravitational potential from the point where the gas cools to the boundary of the region. In general the gravitational energy loss is at most comparable to the thermal energy input, so that estimates for $\dot{M}$ are fairly model independent. Mass flow rates determined in this way vary from anything up to several hundred solar masses per year in a number of cases (Stewart et al. 1984b; Fabian et al. 1985). X-ray spectroscopic observations have confirmed the presence of partially cooled gas in the quantities expected in a cooling flow in a few nearby clusters (Canizares et al. 1982; Lea et al. 1982).

High rates of gas deposition are the origin of much controversy surrounding cooling flows. The cooled gas probably forms into stars and we would expect to see evidence for this star formation. Indeed, if the stars from with the same initial-mass-function (IMF) as applies in the solar neighbourhood, the galaxy at the centre of the flow should be much bluer and, in several cases, much brighter than it is observed to be (Fabian, Nulsen & Canizares 1982; Sarazin & O’Connell 1983). To avoid this difficulty several authors have considered the possibility that some heat source prevents the gas from cooling. Such models generally have difficulty in accounting for the presence of the cooler X-ray emitting gas (Fabian et al. 1984). Bertschinger & Mel'nik (1986) have most recently again raised the question of whether thermal conduction can greatly reduce the cooling rate, but they do not address the issue of how an equilibrium in which thermal conduction almost balances radiative heat loss is established (see discussion of Stewart et al. 1984a).

Fabian et al. (1982) and Sarazin & O’Connell (1983) have argued instead that we should assume that the initial-mass-function for the newly formed stars in a cooling flow must be different from that which applies in the solar neighbourhood, and disk galaxies in general. This should not be surprising since physical conditions are very different in these two types of.
systems. In this talk we consider optical spectra of galaxies at the centres of a number of cooling flows and show they indicate that at least some massive stars are being formed in cooling flows.

There is one more feature of cooling flows, we would like to consider before looking at our new data. It has long been noted that cooling flows are prone to thermal instability (Fabian & Nulsen 1977; Mathews & Bregman 1978). Fabian & Nulsen pointed out that thermal instability in the hot gas could be responsible for the extended system of line emitting optical filaments demonstrated by Lynds (1970) around NGC 1275. Subsequently, extended regions of optical emission have been shown to be a common feature of cooling flows (e.g. Hu et al. 1985). However, it was not until high quality X-ray data was analysed carefully that it was realised that thermal instability plays a dominant role in determining the structure of cooling flows (Fabian et al. 1984; Nulsen 1986; Thomas, Fabian & Nulsen 1987). In fact the term thermal instability is not really appropriate, since the flows must be inhomogeneous mixtures of gas at a range of temperatures. As a consequence cooled gas is being deposited from the flow over a wide range of radii, and the data indicate that the mass flow rate into a sphere of radius \( r \) is approximately proportional to \( r \) (Thomas et al. 1987; the mass flow rate would be independent of radius for a steady homogeneous flow). This means, in particular, that any star formation is also spread throughout a cooling flow.

### Line emission from cooling flows

Extended regions of optical line emission are commonly associated with cooling flows (e.g. Kent & Sargent 1979; Fabian et al. 1981; Heckman 1981; Cowie et al. 1983). Furthermore, the strength of the line emission has been shown to correlate with the X-ray luminosity of these sources (Cowie et al. 1983).

Johnstone, Fabian & Nulsen (1987) report optical spectroscopy of 10 galaxies known to lie at the centres of cooling flows. They also find a correlation between the total cooling rate and the line luminosity. If the line emission is due directly to the cooling of the gas then it should be correlated with the local rate of cooling. The area covered by the spectrograph slit is typically very much smaller than both the region of the steady cooling flow and the angular resolution of the X-ray observations. Johnstone et al. therefore estimate the rate of cooling, \( \dot{M}_c \), in the area covered by the slit by assuming that \( \dot{M} \) is proportional to \( r \). They find that this local cooling rate is also well correlated with the H\alpha luminosity from the flow. The relationship between \( \dot{M}_c \) and the H\beta luminosity provides a test of models for producing the line radiation. A number of mechanisms have been proposed by which the thermal energy of the gas is converted into lines. The luminosity in H\beta can be expressed in terms of the cooling rate as

\[
L(\text{H}\beta) = 9.3 \times 10^{36} H_{\text{rec}} \dot{M} \text{ erg s}^{-1},
\]

where \( \dot{M} \) is in \( M_\odot \text{yr}^{-1} \) and \( H_{\text{rec}} \) is the mean number of times that a hydrogen atom recomines during the cooling. Photoionization by radiation from hotter gas (Binette et al. 1985) andreshocking of rapidly cooling blobs which fall out of pressure equilibrium with their surroundings (Cowie, Fabian & Nulsen 1980) both give values of \( H_{\text{rec}} = 1-2 \), which fall far short of the observed values of 1000 or more when comparing with \( \dot{M}_c \). This suggests that some additional source of ionizing radiation is required to account for the line emission from cooling flows.

Here we will focus on star formation as the possible source of the ionizing radiation required to account for the line emission.

### Star formation

As we have already noted, the bulk of the cooling gas cannot be forming into stars with the initial-mass-function which applies in the solar neighbourhood. Nevertheless, there is evidence of recent star formation in several cooling flows. For example, NGC 1275 at the centre of the Perseus cluster shows an A-type spectrum (Rubin et al. 1977) and the galaxy at the centre of A1795 shows an F-type spectrum (Sarazin 1986). All of the galaxies at the centres of cooling flows have been classified as elliptical and would not normally be expected to show such signs of recent star formation.

Hot young stars have a smaller break in their continuum emission at 4000 Å than the stars of later spectral type which make up elliptical galaxies. Bruzual (1983) uses the quantity

\[
D = \frac{\int_{4050}^{4250} F_\lambda d\lambda}{\int_{3750}^{4050} F_\lambda d\lambda}
\]

as a measure of the break in the continuum, so that the presence of massive young stars is indicated by smaller values of \( D \) than typical. Figure 1 shows \( D \) plotted against \( \dot{M}_c \), the cooling rate in the area covered by the slit. There is a clear trend, with the galaxies having the highest local cooling rates also showing the weakest breaks in the continuum at 4000 Å. This indicates that some massive stars are forming from the cooled gas.

If the line emission is excited by newly formed stars, then there should be a relationship between it and the shape of the 4000 Å break. Kennicutt (1983) has calculated the line luminosity per unit star formation with an initial-mass-function appropriate for a disk galaxy by assuming that all of the radiation in the Lyman continuum from the young stars is converted through photoionization into line radiation. The H\beta luminosity produced is approximately \( 4 \times 10^{40} \text{ erg s}^{-1} M_\odot^{-1} \text{yr} \) of star formation. This gives us an estimate for the star formation rate with the assumed IMF required to excite the observed line emission.

Using Kennicutt's (1983) approximation to the IMF, Bruzual's (1981) main sequence lifetimes and model atmospheres from Kurucz (1979) we can calculate the luminosity produced in any band from a population of stars forming at a constant rate. This gives

\[
L_{\text{new}}(4050-4250) = 6.76 \times 10^{41} \text{ erg s}^{-1} M_\odot^{-1} \text{yr},
\]

\[
L_{\text{new}}(3750-3950) = 6.06 \times 10^{41} \text{ erg s}^{-1} M_\odot^{-1} \text{yr},
\]

from which we immediately get that the continuum break in a constantly forming population of such stars is \( D_{\text{new}} = 1.12 \). This calculation does not include the contribution of stars that...
Figure 1 — The 4000 Å break versus the local cooling rate. This shows the value of \( D \) (see text) plotted against the estimated rate, \( M_v \), at which gas is cooling in the region covered by the slit for a number of cooling flow galaxies. The data are discussed in Johnstone et al. (1987). Points joined by a line are for the same object with differing slit orientations.

have evolved into giants. For massive stars this is not important, but stars of about 1 \( M_\odot \) can make a significant contribution. We assume that these are represented in the old stellar population which makes up the template galaxy.

Using a galaxy where there is no cooling flow as a template we find \( D_T = 2.41 \). Assuming that we can split the band luminosities from a galaxy into a component due to an underlying old stellar population (represented by the template galaxy) and a component due to continuous star formation at a constant rate, \( L_{\text{new}} \), we get

\[
L_{\text{new}}(4050-4250) \times \left( \frac{1}{D_{\text{new}}} - \frac{1}{D_T} \right) = L(4050-4250) \times \left( \frac{1}{D} - \frac{1}{D_T} \right),
\]

where \( D \) is the observed 4000 Å break and \( L(4050-4250) \) is the observed band luminosity. Taking this together with the expression relating \( L_{\text{new}} \) to the star formation rate we can determine the rate of star formation required to give the observed values for \( D \) and the band luminosity.

Under the hypothesis that the line emission and the reduction of the 4000 Å break are both due to star formation with a disk galaxy IMF, the two estimates for the star formation rate must agree. This requires

\[
F(\text{H} \beta) = 0.12 F(4050-4250) \times \left( \frac{1}{D} - 0.41 \right),
\]

where the luminosities have been replaced by fluxes in order to remove distance dependence. Figure 2 shows this relationship for our data. There is reasonable agreement for most, but not all of the galaxies.

Figure 3 shows the star formation rate estimated from the

Figure 2—Two measures of the star formation rate. The quantity plotted on the horizontal axis is proportional to the star formation rate required to account for the filling in of the continuum above 4000 Å relative to normal elliptical galaxies. \( D_0 \) here is the observed value for the 4000 Å break and \( F_\lambda \) is the observed flux between 4050 and 4250 Å. The quantity plotted on the vertical axis is proportional to the star formation rate required to account for the observed \( \text{H} \beta \) flux within the slit. If star formation with a disk galaxy IMF is the cause of both of these effects then the two estimates should be equal (indicated by the solid line; see text for details). Points for the same object are connected.

Figure 3—Star formation rate versus local cooling rate. The star formation rate required to account for the observed \( \text{H} \beta \) luminosity is plotted against the estimated rate of cooling in the region covered by the slit, \( M_v \). The line shows where the star formation rate equals the local cooling rate. The estimated star formation rate is less than or comparable to the rate at which gas is cooling for all the galaxies in our sample. A line connects points for the same object.
HB luminosity plotted against $\dot{M}_*$, The solid line is the locus where the estimated star formation rate equals the local cooling rate. On the evidence of this figure about 10 percent or more of the gas which is cooling locally is being converted into stars with an IMF resembling that for a disk galaxy.

Discussion
In all of the galaxies observed the spectroscopic data are consistent with the line emission being powered by star formation. The photoionization is caused by a small population of hot young stars being formed with an initial-mass-function similar to that which applies generally in disk galaxies. However, the data require only about 10 percent of the gas to be forming stars in this way. The bulk of the cooling gas still cannot be forming stars with a disk galaxy IMF.

The galaxy at the centre of A2029 shows no evidence of line emission even though it has a substantial cooling rate and shows evidence of young stars in the value of its 4000Å break ($D = 2.0$). Under our hypothesis for the origin of the line emission this suggests that the massive star formation may be discontinuous. Images of the line emitting gas clearly indicate that it is not uniformly distributed (e.g. Lynds 1970), suggesting that the star formation is not uniformly spread in space either. The regions of line emission are very unlikely to remain fixed in position, so that the spatial inhomogeneity may fully account for the apparent lack of star formation in the region covered by our spectroscopic slit for A2029. It does not necessarily require fluctuations in the star formation rate on a large scale.

We now have fairly direct evidence that some 10 percent of the inferred cooling gas is forming into stars with a disk galaxy initial-mass-function. The issue remains, however, of what is happening to the bulk of the cooling gas. A sceptic might argue that gas is only cooling at 10 percent of the rate inferred from X-ray observations (e.g. see Bertschinger & Meiksin 1986). But the models proposed to explain the X-ray data without cooling or with greatly reduced cooling still have difficulty in accounting for the presence of the 'partially cooled' X-ray emitting gas. Indeed, the bulk of these models have difficulty in accounting for the presence of any cool gas at all (see discussion in Stewart et al. 1984a).

The observation that some gas is forming into stars with a disk galaxy IMF does nothing to detract from the argument that the gas is indeed cooling at the rates inferred from analysis of X-ray surface brightness data. It remains that the IMF for the bulk of the star formation must be different from that which applies in the solar neighbourhood (and to disk galaxies in general).

Fabian et al. (1982) and Sarazin & O'Connell (1983) point out that physical conditions in a cooling flow are very different from those in the solar neighbourhood. Because the mechanisms which determine the IMF are not understood it is difficult to know what are the important factors. The high temperature origin of the cooled gas probably means that it is depleted in dust (Fabian et al. 1982). This will chiefly affect the energy balance in the gas at low temperatures (Spitzer & Tomasko 1968). The ambient gas pressure is also 100 to 1000 times greater in a cooling flow. This greatly increases the efficiency of radiative cooling at a fixed temperature and also lowers the Jeans mass for the gas.

Our analysis does not indicate how sensitive the relationship given in Figure 2 is to the precise form of the initial-mass-function. It is clear that both measures of the star formation rate are chiefly sensitive to the presence of the more massive stars. Hence although we can say that our data are consistent with some star formation with a disk galaxy IMF we cannot say whether there are separate modes of star formation occurring or simply whether the high mass end of the IMF has a shape something like that for a disk galaxy. The latter is clearly all that we can say about the spatially averaged star formation.

It has been argued that the IMF in our galaxy is bimodal with the relative amounts of star formation in the two different modes varying with time and position (Larson 1986). It may simply be that the massive star formation mode is taken by a smaller fraction of the gas forming stars in cooling flow galaxies.