AGN and Cooling Flows

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Abstract. For two decades the steady-state cooling-flow model has dominated the literature of cluster and elliptical-galaxy X-ray sources. For ten years this model has been in severe difficulty from a theoretical point of view, and it is now coming under increasing pressure observationally. A small number of enthusiasts have argued for a radically different interpretation of the data, but had little impact on prevailing opinion because the unsteady heating picture that they advocate is extremely hard to work out in detail. Here I explain why it is difficult to extract robust observational predictions from the heating picture. Major problems include the variability of the sources, the different ways in which a bi-polar flow can impact on X-ray emission, the weakness of synchrotron emission from sub-relativistic flows, and the sensitivity of synchrotron emission to a magnetic field that is probably highly localized.

1. Introduction

Andy Fabian’s talk was packed with images from the new generation of X-ray telescopes. Images and spectra from Chandra and XMM will enliven the debate between the proponents of the steady-state cooling-flow paradigm and those who argue that unsteady heating by AGN is important. I want to mention some things that need to be borne in mind if the debate is to be fruitful. First let us recall the essentials of the cooling-flow model.

2. The Cooling-Flow Paradigm

The cooling-flow model was first outlined by Cowie & Binney (1977) and was elaborated by Fabian & Nulsen (1977), Nulsen (1986) and others. Extensive reviews can be found in Sarazin (1988) and Fabian (1994).

The X-ray emitting gas is considered to be in a quasi-steady state. It is extremely inhomogeneous in that at any radius there is hot diffuse gas and cooler, denser gas in approximate pressure equilibrium. The coolest gas rapidly cools to very low temperatures and disappears from the X-ray sky. Its place is taken by initially warmer gas, that cools to form cool gas. The place of the warmer gas is taken by slightly warmer gas still, which cools to form just warm gas, and so on right up to the hottest gas. Overall we have a steady inward flow of material of different densities, which gains internal energy as the gravitational field compresses it. Since in any comoving volume of the matter
there is a steady trickle of material ‘dropping out’ at extremely low temperatures and high densities, the density of the X-ray observable gas does not rise as the gas moves inwards as rapidly as it would if the gas were homogeneous.

By adjusting the radial profile of the mass dropout, or, equivalently, the rate $\dot{M}(r)$ at which X-ray observable gas flows in across a sphere of radius $r$, it is possible to obtain a perfect match to the azimuthally-averaged X-ray surface-brightness profile. One finds that $\dot{M} \propto r$ approximately. Once the brightness profile has been fitted to the data and a metallicity chosen, the X-ray spectrum at each radius can be predicted.

3. Problems of the Cooling-Flow Model

Prior to 1987 it was thought that Field’s (1965) thermal instability would naturally give rise to the multiphase medium that permits mass dropout. Malagoli, Rosner & Bodo (1987) showed that Field’s analysis was entirely misleading in a case such as this, in which the cooling medium has a clear gradient in specific entropy and is in approximate hydrostatic equilibrium in a gravitational field. In this case a cool, over-dense parcel of gas (in which the specific entropy will be abnormally low) simply sinks until it reaches the radius at which the bulk of the gas shares its specific entropy. Subsequently, the parcel executes vertical oscillations, that will in practice be strongly damped by turbulence.

While some of us abandoned the cooling-flow model on reading Malagoli et al, others went in with rubber bands to fix the model up. The rubber bands were called magnetic field lines, and they pinned over-dense parcels in place. Clearly, these field lines have to connect cooler gas to the hot embedding matrix, and be fairly straight because they are under significant tension. Consequently, heat will be efficiently conducted down them. Fields of the expected strength can only pin clouds smaller in radius than $\sim 20\text{ pc}$, and these will be evaporated away within a Hubble time unless the thermal conductivity along field lines is several orders of magnitude smaller than expected.

For some years the spectra predicted by the cooling-flow model have conflicted with observation in that the data show fewer photons at low energies, $\sim 1\text{ keV}$, than are predicted. This has been attributed to ‘excess absorption’ by cool gas, probably the very same gas that has dropped out of the flow. The new generation of X-ray telescopes have shown that any absorption is caused by gas at $\sim 10^6\text{ K}$, no cooler gas being detectable (e.g., Böhringer et al., 2000). Searches at radio frequencies for emission by very cold gas have repeatedly failed to detect significant reservoirs of gas, and very strong limits have been set on populations of young stars, from the highest masses down to significantly below one solar mass (Prestwich et al., 1997).

Before the work of Malagoli et al., mass dropout seemed plausible in that the inhomogeneities upon which it depended would be generated by thermal instability from tiny seed inhomogeneities. Once one had read Malagoli et al, it was apparent that one not only had to posit the existence of strongly non-linear inhomogeneities in the initial conditions, but one also had to take steps to prevent their prompt erasure. In these circumstances, it seemed to some of us advisable to stand back and recall that cooling is fastest where the density is highest, and this is known to be at the centre of the cooling flow. Surely cooling
to very low temperatures will occur first at the centre? And will such cooling not
feed the central black hole and provoke it to an outburst? Might that outburst
not restructure the X-ray emitting gas, and thus regulate the cooling process?

4. Heating by AGN

This proposal that cooling flows are in a dynamical equilibrium with a central
AGN has the attraction of a fresh start. It sweeps away cobwebs in the form of
magnetically pinned over-densities and strange absorbing screens. But one has
to admit that at this stage it is little more than a start: the detail is complex and
formidably difficult to work out. Of course we must seek critical confrontation
with the data wherever possible, but we must avoid damning the overall picture
if we find that the data do not support a naive expectation of what the model
might predict.

Working out the observational consequences of AGN feedback on cooling
flows is hard because

- the system is constantly far from a steady state;
- the geometry is inherently complex;
- to predict the radio data one needs to know the distribution of both the
  ultra-relativistic electrons and the magnetic field.

The cooling-flow model is very much simpler and has been rather completely
worked out. Hence the collision between the cooling-flow model and the heating
picture is asymmetrical: on the one side we have a model with well defined
predictions, and on the other a general picture from which it is very hard to
wring firm predictions. We rightly have a preference for the simple over the
complex, for the definite over the vague. Consequently, the majority of people
working in the field have clung tenaciously to the cooling-flow model in the face
of ever-increasing difficulties. Never the less, I submit that the heating model
enjoys a decisive advantage in another important criterion by which we judge
competing theories: a priori plausibility in the light of our knowledge of the
whole of physics and astronomy. We must make a determined effort to work the
picture up into a well-explored model and judge it sternly only when we have
extracted secure predictions from it.

4.1. Time-dependence

The fundamental difference between the heating picture and the cooling-flow
model is that in the former partial derivatives with respect to time will always
be important. One expects an individual source to cycle through a series of
stages. In the first stage the system cools towards a catastrophe. In the second,
the AGN is rejuvenated and blasts its immediate surroundings. In the third
turbulence dies down, and the entropy stratification of the gas is restored before
the first phase of the cycle resumes.

At each stage of the cycle one expects the source to look quite different.
The X-ray gas is expected to respond more slowly than the synchrotron-emitting
plasma, which will respond less quickly than any central continuum source. In
principle it should be possible to make predictions about how many sources should be seen in each stage, but we have neither such predictions nor the demographic knowledge that would be required to test them. Proponents of the cooling-flow model are accustomed to imagining the objects to be in steady states and one has to watch for them implicitly carrying this assumption over to the heating picture.

Some important stages, such as that in which material cools to below 1 keV, may be very short-lived and rarely observed. The phase of violent energy output by the central black hole is likely to be subdivided into extremely short-lived episodes, since the relevant dynamical time is a matter of months only.

4.2. Complex geometry

Even if both the gravitational potential and the central heat source were spherical, the resulting X-ray source would not be because heating from below is inherently unstable: hot plasma will rise in some directions, while cool plasma falls in others. Much of the energy released at the centre is likely to emerge as ordered kinetic energy in a jet or other strongly collimated outflow. One cannot credibly model the system in spherical symmetry (though I have tried! – see Binney & Tabor, 1995). I am skeptical that much useful can be achieved even in cylindrical symmetry (but see D’Ercole & Ciotti, 1998). Fortunately, fully three-dimensional simulations are now just about feasible, and we can hope for fairly realistic models to become available. This will remain a computationally challenging problem for some time, however, because the range of spatial scales and densities involved is extreme – from the parsec scale of the energy source to the megaparsec scale of the X-ray halo; from a proton density in excess of $10^{-8}\, \text{m}^{-3}$ near the centre of the cooling flow to densities many orders of magnitude lower in the plasma ($e\pm$?) of a relativistic jet; from inflow speeds of $\sim 10\, \text{km}\, \text{s}^{-1}$ in the bulk of the cooling flow to the speed of light in the jet. A further complication is the possibility that the IGM becomes multiphase – during the cooling phase this will not occur, but gas heated from below is liable to generate distinct phases, as has long been observed in the disk of the Milky Way.

One should beware simplistic assumptions about how a source’s observable properties will be affected by a jet. Displacement of thermal plasma by relativistic plasma will suppress X-ray emission. On the other hand, X-ray emission will be enhanced when thermal plasma is shocked or pushed up from lower, cooler layers. Correspondingly, X-ray emission will be suppressed when higher-entropy plasma sinks downwards to take up space left by the upward movement of material. From the case of M87 we know too that the synchrotron and inverse-compton processes can sometimes enhance X-ray emission.

4.3. Radio emission

There is a great temptation to feel that one is seeing a true picture of the relativistic plasma when one looks at a map of radio-continuum emission. In fact, as Katherine Blundell (this volume) has emphasized, the synchrotron emissivity at a given wavelength and for a given electron spectrum is a sensitive function of the magnetic field strength. A simple argument suggests that the latter is probably very non-uniform.
This argument starts from the observation that in a perfectly conducting medium the magnetic field obeys the same equation as the vorticity (e.g. Kulsrud et al., 1997). Observations of rivers in spate and wind patterns teach us that in high Reynolds number flows, vorticity is strongly concentrated into sheets and vortex lines; in the language of non-linear systems, vorticity is ‘intermittent’. We must expect magnetic fields in turbulent conducting media to be similarly intermittent, and this expectation is confirmed by recent observations of the Sun (Hagenaar et al., 1999). Hence, when we look at the delicate filamentary pattern of synchrotron emission in an X-ray halo such as that of M87, we are probably seeing merely the regions of enhanced $B^2$, while the relativistic particles are more uniformly distributed. In particular, it is likely that both X-ray emission and synchrotron emission derive from the same plasma; the synchrotron emission comes from the high-energy tail of the particle distribution, and is localized merely because $B^2$ is.

If it is true that ultra-relativistic electrons are space-filling out to the outer boundary of the radio halo (which in the case of M87 lies at more than half the cooling radius), substantial $PdV$ work is likely to have been done by the radio source on the surrounding thermal plasma.

The radiating electrons are ultra-relativistic, and it is dangerous to assume that these exotic particles dominate the total energy in suprathermal particles; certainly in the solar neighbourhood, the cosmic-ray energy is dominated by the least energetic particles. Suprathermal particles with Lorentz factors $\gamma \sim 1$ have extremely long lifetimes because their synchrotron radiation is negligible and they are too fast to be significantly Coulomb scattered. Consequently, they can persist and be dynamically important long after synchrotron emission has become unobservably faint.

Observations of jets suggest that the ultra-relativistic particles that dominate radio maps are generated by jets with bulk Lorentz factors of a few. These jets are unlikely to be produced by the accretion torus around the AGN; they are probably produced by an exotic process, such as the Blandford-Znajek (1977) effect, that taps the rotational energy of the black hole. The fate of the comparable or larger quantity of energy that is released within the accretion disk has long been a puzzle. The ADAF model (Narayan & Yi, 1995) posits that it is swallowed by the black hole. Blandford & Begelman (1999) have strongly criticised this model [which has recently encountered difficulty matching observed spectral energy distributions (Di Matteo et al., 2000)] and argue that the energy is probably carried away by a wind off the accretion torus, rather than swallowed by the black hole. This conjecture chimes with observations of accreting stars, from SS 433 to the sources of Herbig-Haro objects, which imply that an accreting system is invariably associated with a bipolar flow at velocities that range up to the largest Kepler velocity of accreting material.

The implications for the heating picture of a significant fraction of the accretion energy from an AGN emerging as a sub-relativistic bi-polar flow would be considerable. The flow would probably be more steady than the observationally much more conspicuous high-\(\gamma\) jet that would occasionally flicker to life at its centre. It would involve very much more momentum than the high-\(\gamma\) jet, and it would be hard to detect through synchrotron radiation because in the sub-relativistic shocks that would arrest it, very little energy would go into
ultra-relativistic particles. It is likely to generate structure in X-ray maps that is hard to trace in radio maps because it is not associated with strong synchrotron emission. Hence one should treat with caution claims that a weak correlation between the radio and X-ray structures of an object imply that the AGN is not heating the gas.

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