6

Conclusions

Summary

In this chapter I summarise this dissertation and make some concluding remarks.

6.1 Introduction

It is clear that the arrival of the *Chandra* and *XMM-Newton* telescopes have given us a wealth of data on the subject of galaxy clusters. Unfortunately, as is almost always the case in astronomy, the arrival of new data shows that reality is far more complex than our models! We have observed the complex structure of X-ray emitting gas in the *Chandra* images of many clusters, including those which I have studied in this dissertation (Perseus, A1795 and Centaurus), and elsewhere (e.g. Vikhlinin et al. 2001a; Fabian et al. 2001a; McNamara et al. 2000; Markevitch et al. 2000). The spatial resolution of *Chandra* is unsurpassed, and will be for many years since the future planned X-ray missions will focus on effective area and spectral resolution, so *Chandra* will be vital for the understanding of galaxy clusters.

Standard cooling flow models seemed the final description of what was observed in galaxy clusters in the days of *ROSAT* and *ASCA*. Now we must either abandon cooling flows altogether, or explain the lack of low energy emission lines (e.g. Fabian et al. 2001b). If we are to abandon cooling flows altogether, then we must also explain the optical nebulosity, blue continuum emission, UV line emission and infrared emission (Section 1.1.6), not to mention the evidence of gas cooling down to ~ 2 keV.

The next few years will be interesting times for the understanding of cooling flows and galaxy clusters. Data from *Chandra* and *XMM-Newton* will push the theoretical models, and gradually we will understand more about the largest gravitationally bound objects in the universe.

In this dissertation I have examined several clusters and found a variety of structure, including infalling galaxies, radio lobes, filaments, plumes, and metallicity peaks. Some of these features are easily explained, but some are not. This work has made some progress to understanding them. Small-scale structure is what differentiates between clusters: relaxed clusters look very similar on large scales, but *Chandra* has shown unique features in the cores of many clusters. The key to understanding clusters as a whole is understanding the features which make them unique, and what makes them alike.

6.2 Summaries of chapters

6.2.1 Colour maps of cluster cores

In Chapter 2 I made a study of 33 bright clusters from the brightest 55 X-ray clusters, using *ROSAT* archival data. I used the X-ray colour technique of Allen & Fabian (1997) to spatially analyse the clusters for temperature and absorption gradients. The method used in this chapter took account of the spatial structure in the image, rather than forming simple radial contours. Using this data I showed that there is significant evidence for the presence of cooler X-ray gas in the centres of those clusters with known cooling flows. Those clusters without coolings flows did not show evidence for the cooler gas. There was also evidence of increased absorption above galactic column density in those clusters with cooling flows.

6.2.2 Adaptive binning

In Chapter 3 I discussed a method which has been developed for the spatial analysis of X-ray data, which I then demonstrated in use on the Perseus, A1795 and Centaurus clusters (Chapters 4 and 5).

Adaptive binning is a method to bin images according to the local count rate. It attempts to use a bin size which leads to a maximum error in all parts of the image. The method can be used to create X-ray colour maps or intensity maps. It can also be used to generate areas for spectral fitting, or the error on the parameters of spectral fits can be used to choose the bin size.

6.2.3 The Perseus and Abell 1795 clusters

In Chapter 4 I showed the results from *Chandra* observations of two nearby galaxy clusters: the Perseus and Abell 1795 clusters. The image of the core of the Perseus cluster showed the holes which are associated with the radio lobes of 3C 84 and were previously observed by *ROSAT*. The rims of the holes are X-ray bright and consist of cooler gas than their surroundings, indicating that they were not formed as the result of shocks. A spiral structure in the cool X-ray gas was seen in the images, which may have been caused by angular momentum in the cooling flow. A filament-like structure of strong photoelectric absorption was seen across the core of the cluster. The absorption appears to be associated with a small infalling irregular galaxy. Two outer X-ray holes, one of which was previously known, appear to be correlated with spurs of low-frequency radio emission.

The *Chandra* observation of A1795 reveals that there is a 40 arcsec long filament in the core of the cluster. The feature is coincident with a $\mathrm{H}\alpha$+[N II] filament found by Cowie et al. (1983), which was later resolved into two *U*-band components by McNamara et al. (1996a). By fitting X-ray colours to the colours of an adaptively binned image of the cluster, I constructed a temperature map of the region around the filament. The filament has a temperature of 2.5-3 keV, and a mean radiative cooling time of 3×10^8 yr. The cD galaxy at the north end of the filament is probably oscillating through the core of the cluster, and the filament was formed by gas cooling from the intracluster medium.

6.2.4 The Centaurus cluster

In Chapter 5 I showed the analysis of an observation of the Centaurus cluster using *Chandra*. An image of the cluster showed a plume-like feature at the centre of the cluster. The feature has the same metallicity as gas at a similar radius, but is cooler. Radial profiles showed that the previously known steep abundance gradient peaks with a metallicity of $1.3 - 1.8\,\mathrm{Z}_\odot$ at a radius of about 45 arcsec (15 kpc), before falling back to $0.4\,\mathrm{Z}_\odot$ at the centre of the cluster. A radial temperature profile showed that the temperature decreases inwards. I created adaptively binned maps of the temperature, abundance and absorption in the cluster core. The spatial distributions of each of two temperature components were determined. The radiative cooling time of the cooler component within the inner 10 arcsec (3 kpc) is less than 2×10^7 yr. X-ray holes coincident with the radio lobes were found, as well as two outer sharp temperature drops, or cold fronts. The origin of the plume is unclear. The existence of the strong abundance gradient is a strong constraint on extensive convection or gas motion driven by a central radio source.

6.3 Future work

The recent observations by *Chandra* have shown that to understand the structure of galaxy clusters, high spatial resolution is necessary. Detailed imaging of small-scale structure is far easier for clusters which lie close to us at low redshift. Improvements to our knowledge about the processes occurring in the cores of galaxy clusters are likely to come from imaging nearby clusters for extended periods of time, allowing us to look at the properties of the gas in areas with small spatial scales.

An ideal cluster to study is the Perseus cluster. It is the clearest example of a cluster where a central radio source is interacting with the cooling X-ray gas. A detailed study of this cluster may allow us to finally rule out that heating is significant in this cluster. Understanding what fills the radio lobes in NGC 1275 will give a better understanding of radio lobes in general, the energy budget in the cores of clusters, and the nature of the central radio sources in these objects. The metallicity structure in the Perseus cluster would also be an interesting area of study.

The Abell 1795 cluster is also an interesting target since it appears that the cooling gas is located away from the cD galaxy, allowing us to separate galactic phenomena in the cD from the cooling in the cluster. Multi-wavelength studies of the filament will allow us to pinpoint the mechanism for its creation, and understand better the process of star formation from cooling flows.

The Centaurus cluster is a wonderful target. Firstly there is much work to do on the plume, as its origins are not yet understood. Also the presence of the peak in the metallicity away from the core may be telling us something fundamental about the processes of cooling and metal enrichment in galaxy clusters.

There is also work to be done studying complete samples of clusters, such as the brightest 55 cluster sample, looking for trends in their properties, as I did in Chapter 2. The analysis I did was heavily limited by the characteristics of *ROSAT*. An analysis of *Chandra* and *XMM-Newton* data would give a much more complete study, with more spatial and spectral resolution.

The key to understanding cooling flows will by the analysis of grating data (such as that from *XMM-Newton*) in combination with detailed spectral models (e.g. Morris & Fabian, in preparation) and imaging data. As we receive more data from *Chandra* and *XMM-Newton*, we will need to develop more advanced methods of analysing the data spectrally and spatially, possibly from more than one telescope at the same time.