Analyses of Chandra’s first images of cooling flow clusters find smaller cooling rates than previously thought. Cooling may be occurring preferentially near regions of star formation in central cluster galaxies, where the local cooling and star formation rates agree to within factors of a few. The radio sources in central cluster galaxies are interacting with and are often displacing the hot, intracluster gas. X-ray “bubbles” seen in Chandra images are used to measure the amount of energy radio sources deposit into their surroundings, and they may survive as fossil records of ancient radio activity. The bubbles are vessels that transport magnetic fields from giant black holes to the outskirts of clusters.

1 Introduction

The “cooling flow problem,” i.e., the fate of matter putatively cooling below X-ray temperatures in the cores of clusters, has stumped astronomers for over two decades (Fabian 1994). This problem remains unsolved in part because the previous generation of X-ray telescopes was unable to resolve the cooling regions of clusters. The Chandra X-ray Observatory is poised to make great strides toward solving this problem with its unique ability to resolve the inner several tens of kiloparsecs of clusters, where the cooling time is shortest, and recently-accreted, 10−100 K gas and young stars are observed. Chandra’s more than one hundred-fold leap in combined spatial and spectral resolution is allowing astronomers to measure and compare the X-ray cooling rates and optical star formation rates on the same spatial scales. In addition, Chandra is producing crisp images of the hot gas surrounding powerful radio sources in central dominant cluster galaxies (CDGs) located at the bases of cooling flows. This is a significant advance, because radio sources can disturb and heat the surrounding hot gas, and possibly reduce the rate of cooling. The degree of heating and cooling should be imprinted on the temperature and density structure of the gas. When viewed at high resolution, this structure can be compared directly to local heat sources, such as the radio sources themselves and supernovae associated with star formation. As Chandra’s first images of clusters arrived, it became immediately clear that the hot gas in cluster cores is in a complex state, and that Chandra would usher in an era of new and exciting cluster science. Here, I briefly review new Chandra results on accretion-driven star formation and interactions between radio plasma and hot gas in cooling flows as I understand them at this time.
2 X-ray Cooling Rates & Star Formation Rates

The several Chandra studies of cooling flows reported thus far find cooling rates reduced by factors of 5 to 10 compared to those derived from ROSAT data (Fabian et al. 2000a; McNamara et al. 2000a,b; David et al. 2000). Spectroscopic evidence for multiphase, cooling gas is seen only in the inner few tens of kpc of CDGs, where the cooling time is $< 6 \times 10^8$ yr. Although inwardly decreasing gas temperature gradients and cooling times less than 1 Gyr are observed to cluster radii as large as a few tens of kpc, the gas there can often be adequately described using single temperature thermal models (David et al. 2000). How this gas avoids becoming multiphase and cooling to low temperatures is a new challenge posed by the Chandra data (Fabian et al. 2000a).

Although the cooling rates are more moderate than previously reported, cool, multiphase gas (i.e., gas with a range of temperature and density) is seen preferentially in the central regions of CDGs. Several groups have found strong correlations between X-ray cooling rate and the strength of star formation in central cluster galaxies (Fig. 1, McNamara 1997, Cardiel et al. 1998). The long-standing problem has been that the X-ray cooling rates integrated over the entire central $\sim 100$ kpc cooling radius exceeded the star formation rates by one to two orders of magnitude (assuming the local initial mass function and a reasonable range of star formation histories). Furthermore, star formation is generally observed only in the inner few to few tens of kpc, and not over the entire cooling region (Allen 1995; Cardiel et al. 1998, Crawford et al. 1999). Multiphase gas is now seen by Chandra in several clusters in dense clouds and filaments near the sites of star formation. In these regions, the star formation and cooling rates are within factors of $\sim 2$ of each other (McNamara et al. 2000b, Fabian this conference). The preliminary Chandra results bolster the interpretation of Fig. 1 that cooling flows are indeed fueling star formation. But the cooling rates are probably several to several tens of solar masses per year, rather than several hundreds of solar masses per year. Although Chandra analyses have made significant progress toward solving the cooling flow problem, not all of the putatively cooling material has been adequately accounted for, and the data do not by themselves prove that cooling flows are inducing and fueling star formation. The influence of other mechanisms, such as mergers or collisions with gas-rich galaxies, must continue to be explored.
3 Interactions Between Radio Sources and the keV Gas

It is well known that radio sources interact with and may energize the emission nebulae in cooling flows (Baum 1992), and that they play a role in triggering star formation (see references in McNamara 1999). Chandra has since confirmed, in vivid detail, the early ROSAT evidence that radio sources are also interacting with the X-ray-emitting gas in clusters (e.g., Böhringer et al. 1993). In addition to showing that radio sources can have a major impact on state of the hot gas surrounding them, these images are revealing the nature of radio sources themselves. For instance, we do not confidently understand their ages, how long they persist, their composition and kinetic energy content, and how they evolve dynamically. Before we can answer these questions, we need a detailed picture of the physical conditions of the medium in which radio sources move. Chandra is giving us this picture.

3.1 Cavities in the keV Gas

Chandra images of several clusters with X-ray-bright cores have surface brightness depressions—cavities—in the hot, keV gas tens of kpc in size (Fig. 2). Prominent examples are seen in the Perseus cluster (Fabian et al. 2000b), Hydra A (McNamara et al. 2000a), Abell 2597 (McNamara et al. 2000b, 2001), and Abell 2052 (Sarazin 2001). In most cases the cavities are filled with radio emission from the lobes of twin-jet radio sources whose luminosities exceed $10^{42}$ ergs s$^{-1}$. The gas along the rims of the cavities is close to being the coolest gas emitting at keV temperatures in these clusters, and no evidence for strong shocks immediately surrounding the radio jets or lobes has been found. The radio lobes appear to be gently displacing and are confined by the keV gas as they expand.

If the cavities, or bubbles, are supported by internal pressure from magnetic fields, cosmic rays, or a dilute, very hot plasma, they should rise outward into the ICM by buoyancy (Churazov et al. 2000, McNamara et al. 2000). The time required to rise to distances of a few tens of kpc from the nucleus of the host galaxy is $t_{\text{rise}} \sim 10^{7.5-8}$ yr. If this timescale exceeds the on-time of the radio source, the radio surface brightness in the cavities should fade as the energetic particles radiate away their energy, leaving the long-term evolution of the bubble uncertain.

3.2 Ghost Cavities and Radio Source Evolution

CDGs in clusters such as Perseus (Fabian et al. 2000b) and Abell 2597 (McNamara et al. 2000b, 2001) have “ghost” cavities in their X-ray emission that lie well beyond the inner cavities.
associated with their nuclear radio sources. These ghost cavities are devoid of bright radio emission at wavelengths shorter than several centimeters. If ghost cavities are all that remains of a previous radio outburst that occurred $\sim t_{\text{rise}}$ ago, their existence in two clusters implies an evolutionary scenario for powerful radio sources that can be reconciled with the high incidence of radio activity observed in cooling flow CDGs. More than 70% of CDGs in clusters with dense, high surface brightness X-ray emission (cooling flows) harbor relatively powerful radio sources, while less than 20% of CDGs in non cooling flow clusters are radio-bright (Burns 1990). This trend implies that radio sources in cooling flows either persist on Gyr timescales, or they recur with high frequency. Given what little we know of the demographics of bubbles, their existence implies the recurring burst model with a cycling time of $50 - 100$ Myr.

3.3 Energizing and Magnetizing the keV Gas

The sizes and pressures surrounding these bubbles, which are directly measured from Chandra data, provide an estimate of the $PdV$ work done by radio sources on the surrounding medium. In Hydra A, the work is comparable to its radio luminosity for a reasonable range of radio ages. Therefore, there is little compelling evidence for kinetic luminosity that greatly exceeds its radio luminosity. In Abell 2597, the energy associated with its ghost cavities is comparable to the energy of the present-day radio source situated in close proximity to the nucleus. Therefore, in this case the previous radio burst was probably similar to the one we see today.

The energy associated with bubbles is substantial, $\sim 10^{58-59}$ erg. If CDGs produce between 10 – 100 bubbles over their lifetimes, the amount of energy they would deposit into the ICM in the form of magnetic fields, cosmic rays, and heat is $\gtrsim 10^{59-61}$ erg. This energy would be comparable to the total thermal energy of the X-ray-emitting plasma in the inner regions of clusters. Clusters are magnetized (Clarke, Kronberg, & Böhringer 2001), and these bubbles may be vessels that transport magnetic fields from giant, central black holes to the outskirts of clusters.

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