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The X-ray subcluster in A 2256: cluster mergers, cooling flows and diffuse radio sources

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SUMMARY

ROSAT X-ray images of the cluster A2256 have recently resolved the cluster core into two peaks, separated by a projected distance of about 3.5 arcmin. The second peak is interpreted as a lower temperature subcluster in the process of merging. Motivated by this observation, we discuss the fate of the gas in a merging subcluster and show that it may not be shocked during the merger. In particular, if either cluster or subcluster contains a cooling flow the cooling gas will not necessarily be reheated but can thermalize its bulk kinetic energy in the less dense hot gas. As clusters evolve via hierarchical mergers, cooling flows are interrupted as the intracluster medium is stirred up but are then quickly re-established. The main cluster in A2256 has no cooling flow, but we show that the subcluster itself did have. A merger of this type deposits large quantities of cold gas in the core of the main cluster and may promote a cooling flow there. The X-ray subcluster in A2256 coincides with a diffuse radio source and is close to several head-tail radio sources. We suggest that these sources were originally members of the subcluster and that ram-pressure stripping of the surrounding subcluster core has created the diffuse radio source from their lobes.

1 INTRODUCTION

The *ROSAT* X-ray image of the rich cluster of galaxies A2256 shows two peaks of emission (Briel *et al.* 1991). The X-ray emission is modelled as the superposition of two King profiles: a dominant one with a gas temperature of 7.5 keV (Hatsukade 1990), X-ray luminosity of 5.1×10^{44} erg s^{-1} and core radius about 500 kpc; and another, at a projected distance of about 3.5 arcmin (350 kpc assuming $H_0 = 50$ km s^{-1} Mpc^{-1}) to the West with a gas temperature of about 2 keV, X-ray luminosity 9.5×10^{43} erg s^{-1} and core radius of about 400 kpc. Briel *et al.* (1991) suggest that the western peak is the centre of a subcluster merging with the larger cluster, since the southern part of the subcluster emission is sharply compressed. In this paper, stimulated by the X-ray images of A2256 we discuss the behaviour of (sub)cluster gas during a merger.

2 THE MERGER OF A SUBCLUSTER

We first consider a very simple model for a subcluster merger, and at the end of this section discuss the observations of A2256 in more detail. We model the gas in the cluster as isothermal, confined in an isothermal potential with velocity dispersion σ, core radius r_0 and gas density n_0 $(r/r_0)^{-2}$ at radius r. The same parameters for the subcluster are denoted by a prime. We take $n'_0 \approx 2n_0$, $r'_0 \approx 0.5r_0 \approx 250$ kpc and $\sigma'/\sigma \approx 0.5$. The density within the core radius will be nearly constant if the (sub)cluster has no cooling flow. If a cooling flow is present then the gas temperature falls and the density and pressure rise within the central few hundred kiloparsec as the cooler gas responds to the shallow potential within the core radius. We assume that the subcluster is falling on a radial orbit at velocity v, where $v \sim \sigma$ so that the merger is transonic and ram pressure is comparable to the thermal pressure of the cluster gas.

Gas is ram-pressure stripped from the infalling subcluster if the ram pressure of the cluster gas exceeds the gravitational restoring force per unit area given by the subcluster potential. For distributed hot gas in a spherical cluster this is comparable to the pressure in the subcluster (Takeda, Nulsen & Fabian 1984). Thus, when the subcluster centre has reached radius r in the cluster, its gas is stripped down to subcluster radius r'_s, where

$$\frac{r'_s}{r} \approx \frac{r'_0}{r_0}\left(\frac{n'_0}{n_0}\right)^{1/2}\frac{\sigma'}{v}. \tag{1}$$

The gravitational field of the cluster dominates over that of the subcluster for r' outside r'_t, given by

$$\frac{r'_t}{r} \approx \frac{\sigma'}{\sigma}. \tag{2}$$

Stripped gas is decelerated when it has interacted with its own mass. Comparing column densities, we find that gas stripped from radius r' in the subcluster is slowed down by the time it has fallen to radius r in the cluster, where

$$\frac{r'}{r} \approx \left(\frac{r'_0}{r_0}\right)^2 \frac{n'_0}{n_0}. \tag{3}$$

Stripped gas will be broken up into smaller blobs by Kelvin–Helmholtz instabilities (Nulsen 1986) and may therefore be stopped sooner than this. Whether complete mixing takes place, or the cooler subcluster gas remains as an emulsion of cooler blobs, depends on the role of magnetic fields and thermal conduction. It must be strongly suppressed in the intracluster medium in order for cooling flows to occur and we assume that it is suppressed during the merger.

The pressure gradient across the subcluster gas adiabatically compresses and decelerates it, eventually pushing it out of its local gravitational well. A shock develops only if the ram pressure (i) exceeds the thermal pressure of the subcluster gas, and (ii) increases at a faster rate than pressure changes can propagate across the subcluster gas, i.e. $P/(dP/dt) \gtrsim$ sound crossing time, which implies that

$$\frac{r'}{r} \gtrsim \frac{\sigma'}{v}. \tag{4}$$

For the typical parameters we have suggested, the values of r'/r in equations 1–4 are all within a factor two of each other and uncertain by a similar factor. Gas is progressively stripped from the subcluster, to subcluster radius $r' \approx r/2$ when it is at radius r in the cluster. Therefore, as the subcluster falls it distributes its gas within an approximately conical envelope with apex on the cluster centre. Since clusters have a radial gas density profile that decreases gradually rather than abruptly, infalling subcluster gas experiences a gradual rise in thermal and ram pressure and is not strongly shocked. When the gas is stripped down to the gravitational core of the subcluster (by which time this has nearly reached the cluster core), the remaining gas is stripped as a single blob.

When the subcluster is at large radii (beyond a megaparsec from the core of the cluster), shocks may ocur in the outer gas if the gas temperature there is low and the ram pressure build-up is discontinuous or sudden. This happens if clusters have distinct 'edges', as expected if the gas temperature decreases with radius. Regardless of whether shocks occur, that part of the kinetic energy of the merging gas which is not used in doing PdV work in compressing the gas must eventually be converted into thermal energy via dissipation, probably on small scales following a turbulent cascade. Shocks and turbulence dissipate most of the energy in the less dense hot gas.

The massive central galaxy in the subcluster probably spirals into the central galaxy of the cluster on a free-fall time. If the former is comparable in mass and luminosity to the latter, and the impact parameter is small, then we expect the envelope of the final central cluster galaxy (of the now merged cluster and subcluster) to be extended along the impact direction (as discussed for the case of A1795 by Johnstone, Naylor & Fabian 1991).

If either cluster or subcluster contains a cooling flow then the cooling gas will not be reheated. Stirring during the merger may interrupt the cooling flow(s), but cooler gas will fall slowly into the core of the merged cluster and re-establish a focused cooling flow as soon as the central galaxies have merged.

We now discuss the A2256 merger in more detail. Assuming that bremsstrahlung is the dominant X-ray emission process and taking the peak surface brightness of the X-ray subcluster and counts-to-luminosity conversion factors from the work of Briel *et al.* (1991), we estimate that the gas density at a subcluster radius of 100 kpc is about 5×10^{-3} cm^{-3}. Its cooling time is then about 5×10^9 yr and we infer that the subcluster has had a cooling flow. The X-ray properties of the subcluster are therefore very similar to those of the optically-poor cluster MKW3s (as noted on the basis of the X-ray luminosity by Briel *et al.* 1991), which has a cooling flow of $\sim 150\ M_\odot$ yr^{-1} (Canizares, Stewart & Fabian 1983). The density of the gas in the main cluster is $\sim 10^{-4}$ cm^{-3} at 2 Mpc, rising to $\sim 10^{-3}$ cm^{-3} at 500 kpc (Fabricant, Kent & Kurtz 1989). Its core gas is less dense and hotter than that of the subcluster, meaning that the central cooling time is about 2×10^{10} yr.

The gas in the core of the subcluster has a much lower entropy than that in the cluster. If we use the above numbers and assume that the merger is adiabatic, subcluster core gas (even from a radius of ~ 100 kpc) will still be much cooler than the existing gas by the time it reaches the cluster core, by a factor of ~ 3. Large quantities of cooler gas will therefore be deposited in the core of A2256, and may promote the onset of a massive cooling flow there. This observation indicates that the initial conditions of the A2256 merger differ from those used in the 30 hydrodynamical simulation of the formation of a cluster by Evrard (1990a, b). His simulation shows the infall of a subcluster and demonstrates that the infall is approximately adiabatic, but starts with the subcluster core gas on a higher adiabat and therefore compresses it to a slightly higher temperature than the cluster core.

3 RADIO SOURCES IN A2256

We now consider the radio sources in A2256. The X-ray subcluster is just to the north of several head-tail radio sources (A, B, and C in the notation of Bridle & Formalont 1976) which have their tails pointing back towards the subcluster gas. It is centred 1.5 arcmin southeast of where the neck of source C joins with a large (5×10 arcmin^2, or about 500×1000 kpc^2) diffuse radio source which is coincident with the northern half of the X-ray subcluster. The radio appearance of the region, and the highly compressed X-ray contours just to the south of the subcluster peak in the image by Briel *et al.* (1991), suggest that the subcluster gas is now being stripped from the core of the subcluster, which is moving south and therefore merging with a non-zero impact parameter. The galaxies identified with radio sources A, B and C were probably members of the subcluster. Stripping of the subcluster gas may have created the diffuse radio source from their lobes. The subcluster lacks an obvious massive central galaxy, which could have been the galaxy identified with A (probably including NGC 6331), thereby demonstrating that the gas has been pushed out of the gravitational well. All four galaxies associated with the radio sources A (×2), B and C that have measured redshifts are moving towards us relative to the mean velocity of the cluster, 17 431 ± 147 km s^{-1} (Fabricant *et al.* 1989), and have velocities between 16 818 and 17 418 km s^{-1} (Bridle & Formalont 1976). The stripping of the subcluster has turned the radio sources in these galaxies into head-tail ones; it may also have stimulated the activity in their nuclei.

4 DISCUSSION

The discovery of the colder (kT ~2 keV versus 7 keV) X-ray subcluster in A2256, together with the radio evidence which suggests that the gas is in the process of being ram pressure stripped from the gravitational well of the subcluster (and is not a chance projection of a more distant subcluster), has shown that low entropy gas in the cores of clusters is not necessarily shock heated during the merger. We suggest that if either or both of a merging cluster and subcluster contain a cooling flow then the merger may disrupt the focused cooling flow as cooling gas is stirred up, but that the flow will be re-established in the merged cluster as the central galaxies themselves merge. The high observed frequency of cooling flows in low-luminosity clusters (Arnaud 1988; Pesce *et al.* 1990; Stewart, Edge & Fabian 1991) means that such mergers are common. Mergers may contribute to the turbulence observed to be present in many cooling flows (Heckman *et al.* 1989; Loewenstein & Fabian 1990), and will produce the required inhomogeneous, multiphase gas distribution both by adiabatically stirring the existing cluster gas (which even if originally homogeneous will have a radial entropy gradient), and by directly introducing cooler gas.

The infall of a small subcluster is unlikely to disrupt a cooling flow in the main A2256 cluster so the absence of one now suggests that there was not one before. Only when two clusters with similar properties collide can we expect a major disruption of their cooling flows (McGlynn & Fabian 1984). Since clusters appear to grow by the merger of subclusters (Edge *et al.* 1990), we infer that A2256 has previously had such an 'equal' collision. In most cases, both the main cluster and the subcluster will have cooling flows and the merger will result in them being combined as a larger, more inhomogeneous and turbulent flow around the central galaxy of the main cluster.

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