The evolution of cluster X-ray sources: subcluster collisions

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Summary. We investigate the evolution of cluster X-ray sources with a three-dimensional hydrodynamical numerical technique. We have paid particular attention to the behaviour of intracluster gas during the merger of two subclusters to form a single cluster. We find only a small enhancement in X-ray luminosity during the merger. The evolution of the X-ray luminosity subsequent to the merger is very similar to that found previously with a one-dimensional code.

1 Introduction

Evolutionary models of the intracluster medium (ICM) in rich clusters of galaxies have been constructed by Gull & Northover (1975), Lea (1976), Takahara et al. (1976), Cowie & Perrenod (1978, henceforth Paper I), and Perrenod (1978, henceforth Paper II). In Paper I it was found, in agreement with the results of Gull & Northover and Takahara et al., that the ICM evolves quasi-statically for both infall and mass injection as the source of intracluster gas. In Paper II an evolving cluster potential was employed and it was found that the X-ray properties of the ICM change significantly with time; X-ray luminosities, for example, increase by an order of magnitude from the epoch $z = 1$ until the present.

All of the above-mentioned models have been constructed using one-dimensional hydrodynamic codes, either finite difference or beam scheme codes. In this paper we present models constructed using a three-dimensional smoothed particle hydrodynamics (SPH) code. We find that the basic character of the numerical solutions presented in Paper II is reproduced rather closely by the SPH technique.

In particular, we investigate the phase of violent relaxation of a cluster. In $N$-body experiments (White 1976; Aarseth, Gott & Turner, in preparation) it is found that clusters grow by ‘bootstrapping’ (see Press & Schecter 1974) their way through stages of subclustering. In White’s 700-body simulation of the Coma cluster, he found that two subclusters of approximately equal mass merge at $t \sim 9 \times 10^9$ yr after the start of the calculation. The

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merger is followed by violent relaxation of the central regions of the cluster. Following the phase of violent relaxation, the cluster evolves more slowly via galaxy two-body encounters.

Here, we have followed the evolution of the ICM closely during the phases of subcluster collision and violent relaxation. We have collided two individual subclusters each of mass one-half the Coma cluster mass and each with its own ICM. Subsequent to the collision, we have treated the evolution of the ICM in the potential of the resultant single cluster. We are principally interested in the behaviour of the ICM during the relatively short (~ $2 \times 10^9$ yr) collision interval. We find that the enhancement in the X-ray luminosity during the merger of the two subclusters is modest, and that after the merger the luminosity track obtained from SPH models of a single cluster is similar to that from the models in Paper II.

In Section 2 we briefly discuss the SPH technique and its limitations. In Section 3 we present the results of several of our models, and in Section 4 we summarize our results.

2 The SPH technique and physical assumptions

The SPH technique provides an inexpensive method of obtaining at least a rough idea of the behaviour of fluids in three dimensions. The technique has been successfully applied to several non-spherically symmetric problems involving self-gravitating polytropes (Gingold & Monaghan 1977, 1978). The principle features of the method are that the fluid is replaced by a discrete set of fluid elements and that the density and other physical fields are obtained by a statistical smoothing procedure from the positions and properties of these sample fluid elements. The hydrodynamical equations are replaced by a simple set of Newtonian equations of motion for the fluid elements (or particles). Three-dimensional problems involving rotating polytropes have been successfully treated employing as few as 80 particles. It has further been shown that fields other than that of the distribution of matter can be handled by this sort of technique (Gingold & Monaghan 1977 — Magnetic Fields; Lucy 1977 — Entropy). The statistical smoothing procedure involves a parameter $h$, the smoothing length scale. It is clear from the discussion given in Gingold & Monaghan (1977) that one cannot hope to look at detail on a scale smaller than this length (this is analogous to the cell size of finite difference techniques) and that one may reduce $h$ as the number of particles employed is increased. Thus physical phenomena, such as shocks, which may occur within a region of size less than $h$, may be suppressed or smoothed away. The SPH technique has successfully treated shocks in one dimension (Monaghan, private communication). At this stage, however, it appears that only by substantially increasing the number of particles in the computation may we hope to delineate such features in three dimensions.

To simplify the treatment of the present problem we have assumed a polytropic relation between pressure and density $P = K \rho^\gamma$ where $K$, the specific entropy, is initially fixed by setting the initial temperature of the intracluster gas at the centre of each subcluster to $10^7$K. We have studied subcluster collisions with $\gamma = 1.2$ and 5/3. Recent observational evidence tends to favour values of $\gamma$ nearer to 1 (isothermal) than to 5/3 (Malina et al. 1978; Mushotzky et al. 1978). An approximately isothermal atmosphere may arise if thermal conduction or radiative cooling are significant.

The equations of motion used in this study are similar to those of the appendix of Gingold & Monaghan (1978) except the gravitational force on each particle arises solely from the background subcluster or cluster potentials (see below). We roughly model the fluid viscosity by the inclusion of a damping term in the equations of motion. More sophisticated treatments of dissipation could possibly be achieved by making use of the smoothed velocity field or by considering pair interactions between particles. For the present study it was considered adequate to include, for each particle, a damping of the
velocity relative to the centre of mass of the appropriate subcluster. The time-scale of this
dissipation (0.4 \times 10^9 \text{yr}) was chosen so as just to avoid the gas bouncing as it fell into the
cluster potential. At each time step, the kinetic energy removed from each particle by the
damping was computed and added to the internal energy by increasing the specific entropy
\( K_t \) of each particle.

We have taken two identical subclusters, each pervaded by gas, and examined the
behaviour of this gas as the subclusters collide. The gas is initially distributed in the same
way as the galactic mass. This is achieved by distributing our particles randomly in space
according to the density law given in the following paragraph. After the subclusters merge,
we have followed the behaviour of the gas as the potential of the single cluster evolves.

The kinematic and gravitational properties of the colliding subclusters were taken from
White’s (1976) 700-body cluster simulation. In that study, two major subclusters, separated
by 4 Mpc, developed by \( \sim 7 \times 10^9 \text{yr} \) (see figure 1(c) of White’s paper). These subclusters
merged some \( 2 \times 10^9 \text{yr} \) later. We assume that the initial individual subcluster gravitational
potentials are produced by a galactic density distribution of radial dependence:

\[ \rho = \rho_0 / (1 + r^2 / a^2)^{3/2} \]

with \( \rho_0 = 2.7 \times 10^{-26} \text{g cm}^{-3} \), \( a = 0.55 \text{Mpc} \), and a radial cut-off at 3 Mpc. Each subcluster has
a mass \( 1.2 \times 10^{15} M_\odot \). The associated mass in the form of gas was taken as 1.5 per cent of this.

Following the merger of the subclusters, we have obtained a varying potential from a table
kindly provided by S. Aarseth. This table gives the radii of spheres which contain various
fractions of the cluster mass as a function of time from White’s calculation (see Perrenod
1978 for details).

During the collision phase the smoothing length scale \( h \) was allowed to vary and was
computed from a length scale determined by the gravitational potential energy of the gas.
Following the merger \( h \) was held constant.

3 Results

We have constructed several models; parameters of and results from six of these are
presented in Table 1.

Model 1 is an ICM model with \( \gamma = 5/3 \) for a single cluster with an evolving potential
beginning at cosmic time \( t_0 = 7.2 \text{\,(} t_0 = t/10^9 \text{yr)} \). This model was constructed in order to
facilitate comparison with the spherically symmetric models of Paper II. We find that the
luminosity evolution is similar in both studies. In Fig. 1 we have plotted the total thermal
bremsstrahlung luminosity above 2 keV, \( L_2 \), as a function of time for each of the six models
presented in this paper, and for model 13 of Paper II as well. The Born approximation to the
Gaunt factor was employed, and a He abundance of 10 per cent by number was assumed, in
the calculation of \( L_2 \).

Models 2–6 simulate collisions between two subclusters, followed by the evolution of a
single cluster containing the total mass of the system. In model 2, two equal mass subclusters
 collide with a relative speed of 2 Mpc/billion yr (\( \sim 2000 \text{km/s} \)). The \( \sim 30 \text{ per cent peak to peak variations of } L_2 \) after \( t_0 = 9 \) in Fig. 1 are driven by the temporal variations of White’s
potential. The typical time-scale for the oscillations is \( 1–2 \times 10^9 \text{yr} \).

In Fig. 2 we present a snapshot of the 200 fluid elements of model 2 at the time \( t_0 = 8.0 \),
i.e. during subcluster merger. The viewing orientation is perpendicular to the axis which
joins the two subclusters. It can be seen that the fluid density in the interface region
between the subclusters is not greatly enhanced, and in fact is less than the density at the
centre of either subcluster.
Table 1. Properties of the models.

<table>
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<tr>
<th>Model no.</th>
<th>1</th>
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<th>4</th>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>$\rho$ (10^{-3} \text{ cm}^{-3})</td>
<td>1.2</td>
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<td>0.69</td>
<td>1.42</td>
<td>0.65</td>
<td>0.92</td>
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<td>$T_\phi$ (10^7 \text{ K})</td>
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<td>7.1</td>
<td>6.3</td>
<td>3.6</td>
<td>5.3</td>
<td>10.0</td>
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<td>$R_{\phi}$ (Mpc)</td>
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<td>0.54</td>
<td>0.57</td>
<td>0.64</td>
<td>0.34</td>
<td>0.37</td>
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<tr>
<td>$h$ (Mpc)</td>
<td>0.24</td>
<td>0.24</td>
<td>0.12</td>
<td>0.22</td>
<td>0.26</td>
<td>0.24</td>
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<td>$\Delta KE$ (10^{64} \text{ erg})</td>
<td>4.8</td>
<td>6.3</td>
<td>8.1</td>
<td>7.5</td>
<td>1.6</td>
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<td>$\log L_{\phi}$ (erg/s)</td>
<td>43.91</td>
<td>43.90</td>
<td>44.02</td>
<td>43.96</td>
<td>43.52</td>
<td>44.04</td>
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$t_\phi^*$ = 17

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<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>$\rho$ (10^{-3} \text{ cm}^{-3})</td>
<td>4.1</td>
<td>1.9</td>
<td>–</td>
<td>9.7</td>
<td>0.42</td>
<td>1.8</td>
</tr>
<tr>
<td>$T_\phi$ (10^7 \text{ K})</td>
<td>17</td>
<td>22</td>
<td>–</td>
<td>9.9</td>
<td>30</td>
<td>22</td>
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<tr>
<td>$R_{\phi}$ (Mpc)</td>
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<td>0.19</td>
<td>0.35</td>
<td>0.26</td>
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<tr>
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<td>13</td>
<td>–</td>
<td>19</td>
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<tr>
<td>$\log L_{\phi}$ (erg/s)</td>
<td>44.72</td>
<td>44.27</td>
<td>–</td>
<td>45.38</td>
<td>43.57</td>
<td>44.19</td>
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</table>

Model

(1) Single cluster (2.4 \times 10^{13} M_\odot) 200 fluid elements.
(2) Subcluster collision $\gamma = 5/3$. $V_{\text{collision}} = 2 \text{ Mpc}/10^8 \text{ yr}$, 200 fluid elements.
(3) Same as model 2 but 800 fluid elements.
(4) Same as model 2 but $\gamma = 1.2$.
(5) Same as model 2 but $V_{\text{collision}} = 6 \text{ Mpc}/10^8 \text{ yr}$.
(6) Same as model 2 but extra damping at ICM interface.

* Epoch of model in units of 10^9 yr.
† Central hydrogen number density of gas, assuming 10 per cent helium by number.
‡ Gas temperature at the centre.
§ Radius at which the gas density falls to half its central value. For $t_\phi = 9.2$ the upper value refers to the half-density radius along the axis between the subcluster centres; the lower value is for either of the perpendicular axes. For $t_\phi = 17$ a single value describes the spherically symmetric atmosphere.
‖ Smoothing length scale.
** Total amount of kinetic energy damped into thermal and binding energy.
†† X-ray luminosity above 2 keV.

The X-ray surface brightness of model 2 at $t_\phi = 9.0$, as a function of position along the $z$ axis, is shown in Fig. 3. The luminosity of the interface region ($z \sim 0$) is smaller than the luminosity of either subcluster.

Model 3 is identical to model 2, except that as a check on the reliability of using 200 particles in the SPH method, this model was constructed with 800 particles. This also allows us to decrease the smoothing length scale $h$ by a factor of 2. This model was run only until the collision epoch. Its behaviour is very nearly identical with model 2. Thus, 200 particles appear to be sufficient for a good description of ICM evolution.

Model 4 again has parameters the same as those of model 2, except that $\gamma = 1.2$ rather than 5/3. With this more nearly isothermal equation of state, we find that the run of luminosity is very similar to that of model 2, until the merger at $t_\phi \sim 9$. However, for $t_\phi > 9$, the model with $\gamma = 1.2$ has a higher luminosity at each epoch. At the end of the calculation model 4 is an order of magnitude brighter. As expected (cf. Paper II and Lea 1976) the central density is larger in this model, while the central temperature is lower. The higher luminosity is a result of the significantly enhanced central density for this model.
Figure 1. The X-ray luminosity above 2 keV versus time for each of the models in this paper. For comparison, the run of luminosity for a spherical infall model constructed in Paper II, 13, is also shown.

The parameters of model 5 are also similar to those of model 2 except the collision speed is three times as great. The rise in luminosity is more rapid in this case and the luminosity is less variable in the later stages. This occurs because the gas distribution is more extended and thus less susceptible to changes in the potential.

Since one might expect a larger amount of dissipation at the interface between the two colliding intracluster media, we have introduced an extra damping of the velocity along the
Figure 2. A snapshot of the 200 fluid elements of model 2 at the time $t = 8 \times 10^9$ yr, as viewed from an orientation perpendicular to the axis defined by the subcluster centres.

Figure 3. The surface brightness, above 2 keV, along the axis separating the two subcluster centres; the profile is for the same epoch and viewing orientation as in Fig. 2.
line joining the two subclusters. This damping is confined to a zone of width 0.3 Mpc centred between the subclusters. Model 6 is one such model with this extra damping having half of the magnitude of the damping otherwise employed throughout this study. The introduction of this extra damping leads to little change during the collision phase; in fact, increasing this damping by as much as a factor of 40 has little effect.

Models 3–6 have snapshots during the merger phase which are qualitatively similar to Fig. 2, and surface brightness profiles at that phase which are similar to Fig. 3, in harmony with the moderate increase of the luminosity during this phase. In no case is an interface region of high density and luminosity formed.

4 Conclusions

Our basic results are:

1. The run of X-ray luminosity with time for models generated with the SPH technique is basically similar to those of Paper II.

2. During the collision and violent relaxation phase no significant enhancement in X-ray luminosity is found in comparison with the single cluster case.

3. Oscillations of the X-ray luminosity of up to half an order of magnitude, on time-scales of $\sim 2 \times 10^8$ yr, occur in response to oscillations in the cluster potential of White’s simulation.

While the SPH technique does not readily produce shocks, it successfully models the gross properties of the ICM. Thus, it should be quite suitable for modelling the basic character of the evolution of intracluster gas in highly flattened clusters such as Perseus.

These results provide support for the evolutionary calculations in Paper II and, in particular, for the idea that cluster X-ray luminosities should be significantly less in the past than at present, even during the violent relaxation phase of cluster evolution. For White’s 700-body model, as applied to the Coma cluster, the merging of the two subclusters occurs at a redshift of $1.25 > z > 0.32$ for $0 < q_0 < 0.5$ and $H_0 = 50$ km/(s Mpc). The rise in luminosity is quite steep during this phase; any individual cluster would be characterized by the redshift at which its X-ray luminosity undergoes this sharp increase.

For the cluster ensemble, any characteristic redshift cut-off, beyond which the number of high luminosity X-ray clusters drops off sharply, will of course tend to be smeared out, since clusters have a broad distribution of dynamical ages. If, in spite of this, such a characteristic redshift can be identified, it may provide cosmological information, since one could make a correspondence between the typical cluster relaxation time (from dynamical theory) and the redshift.

In addition, we may predict that the X-ray luminosity function of clusters will be steeper at large redshifts ($z \geq 0.5$ or larger, depending on $q_0$) than at present. This occurs because single bright clusters ‘break up’ into two or more fainter subclusters as one looks back in time. This effect may be difficult to observe, since the luminosities drop sharply (going towards higher redshift) at the time of break-up, and since arcminute or better resolution will be necessary to resolve the subcluster cores.

Acknowledgment

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References