Simulating the toothbrush: evidence for a triple merger of galaxy clusters

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ABSTRACT
The newly discovered galaxy cluster 1RXS J0603.3+4214 hosts a 1.9 Mpc long, bright radio relic with a peculiar linear morphology. Using hydrodynamical N-body adaptive mesh refinement simulations of the merger between three initially hydrostatic clusters in an idealized set-up, we are able to reconstruct the morphology of the radio relic. Based on our simulation, we can constrain the merger geometry, predict lensing mass measurements and X-ray observations. Comparing such models to X-ray, redshift and lensing data will validate the geometry of this complex merger which helps in constraining the parameters for shock acceleration of electrons that produces the radio relic.

Key words: hydrodynamics – galaxies: clusters: general – galaxies: clusters: intracluster medium – large-scale structure of Universe – X-rays: galaxies: clusters.

1 INTRODUCTION
Some merging galaxy clusters host diffuse extended radio emission, the so-called radio haloes and relics, unrelated to individual galaxies. The origin of these haloes and relics is still debated, although there is compelling evidence that they are related to cluster mergers (Ensslin et al. 1998; Miniati et al. 2001; Hoeft & Brüggen 2007; Hoeft et al. 2008; Pfrommer, Enßlin & Springel 2008; Battaglia et al. 2009; Skillman et al. 2011; Vazza et al. 2012). van Weeren et al. (2012) present detailed Westerbork Synthesis Radio Telescope (WSRT) and Giant Metrewave Radio Telescope (GMRT) radio observations between 147 MHz and 4.9 GHz of a new radio-selected galaxy cluster 1RXS J0603.3+4214, located at a redshift of 0.225. The cluster hosts a large bright 1.9 Mpc radio relic, so-called toothbrush for its shape, as well as an elongated ∼2 Mpc radio halo, and two fainter radio relics (van Weeren et al. 2012). Part of the main radio relic has a peculiar linear morphology. The cluster is detected as an extended X-ray source in the ROSAT All-Sky Survey with an X-ray luminosity of $L_{X,0.1-2.4\text{keV}} \sim 1 \times 10^{45}$ erg s$^{-1}$. An overlay of the radio and X-ray data is shown in Fig. 1. The distorted intracluster medium (ICM) is clearly elongated along the north–south and possibly in the east–west directions, indicating a complex merger. V-, R- and I-band 4.2-m William Herschel Telescope (WHT) images confirmed the presence of a large galaxy cluster.

For the bright radio relic, a clear spectral index gradient from the front of the relic towards the cluster centre is observed. Parts of the relic are highly polarized with a polarization fraction of up to 60 per cent. A model in which particles are (re)accelerated in a first-order Fermi process at the front of the relic provides the best match to the observed spectra. The orientation of the bright relic and halo indicates a north–south merger, but the peculiar linear shape and the presence of another relic, perpendicular to the bright relic, suggest a more complex merger. Deep X-ray observations as well as lensing studies will be needed to completely understand the dynamics of this cluster. Here we attempt to model this peculiar object using the hydrodynamic adaptive mesh refinement (AMR) code FLASH v3.3. In particular, we would like to model (i) the linear morphology of the relic and (ii) its orientation with respect to the X-ray emission. As a result, we will be making predictions about the mass profile that may be detected via gravitational lensing. Understanding the dynamics of the gas in this object is crucial for understanding the physical conditions under which relics are formed.

There exist a number of simulations of cluster mergers (Roettiger, Burns & Loken 1993; Schindler & Mueller 1993; Burns et al. 1994; Pearce, Thomas & Couchman 1994; Roettiger, Loken & Burns 1997; Ricker 1998; Roettiger, Stone & Burns 1999; Roettiger & Flores 2000; Takizawa & Naito 2000; Ricker & Sarazin 2001; Ritchie & Thomas 2002; Poole et al. 2006; ZuHone et al. 2009; ZuHone, Markevitch & Johnson 2010; van Weeren et al. 2011; ZuHone 2011).

Cluster mergers can decouple the baryonic matter component from the dark matter (DM), which causes an offsets between the gravitational centre (measured from lensing) and X-ray centre of the cluster. This was first observed for the ‘Bullet cluster’ (1E 0657−56; Clowe et al. 2006). Springel & Farrar (2007) presented hydrodynamical models of galaxy cluster mergers to reproduce the dynamical state and mass models (from gravitational lensing) of the ‘Bullet’ cluster (1E 0657−56). Mastropietro & Burkert (2008) presented detailed N-body/smoothed particle hydrodynamics...
simulations of the system. In the following, we describe our attempts to reproduce the event that could form the ‘toothbrush cluster’.

2 METHOD

We performed our simulations using FLASH v3.3, a parallel hydrodynamics astrophysical simulation code developed at the Center for Astrophysical Thermonuclear Flashes at the University of Chicago (Fryxell et al. 2000). In our simulations, the grid was refined adaptively using standard criteria based on density gradients. FLASH solves the Euler equations of hydrodynamics using the piecewise parabolic method (PPM) of Colella & Woodward (1984), which is ideally suited for capturing shocks. FLASH solves for the motion of the particles using the particle mesh method to compute the gravitational forces. We set up three idealized galaxy clusters in a cubical box of size \((9 \text{ Mpc})^3\), in our fiducial run resolved with an effective resolution of \((512)^3\) cells. This yields a minimum cell size of 17.5 kpc. The DM in each cluster is represented by \(10^6\) particles.

For simplicity, we follow ZuHone, Lamb & Ricker (2009) and use a mathematical simplicity of the corresponding distribution functions. The density \(\rho\) of the DM is assumed to be isotropic, i.e. \(\sigma_u = \sigma_\phi\), and the positions and velocities for the DM particles are set up as outlined in Kazantzidis, Zentner & Kravtsov (2006). For the particle positions, a random deviate \(u\) is uniformly sampled in the range \([0, 1]\) and the function \(u = M_{\text{DM}}(r)/M_{\text{DM}}(r_{\text{max}})\) is inverted to give the radius of the particle from the centre of the halo. The distribution function of any steady-state, spherically symmetric system depends on the phase-space coordinates only through the integrals of motion \(E\) and \(L\), where \(E = \psi - \frac{1}{2}v^2\) is the relative energy, \(L = r\psi\) is the angular momentum of a particle (Binney & Tremaine 1987) and \(\psi(r)\) is the relative gravitational potential, and \(v_t\) is the tangential velocity. We initialize particle velocities by choosing \(L = 0\), since cosmological simulations point to low spin parameters for cluster-sized DM haloes (e.g. Gottlöber & Yepes 2007).

The total mass distribution determines the gravitational potential, and via the constraint of hydrostatic equilibrium of the gas within this potential, the pressure profile is uniquely determined. To obtain densities, we have to impose a gas temperature profile. We assume an isothermal cluster with the temperature set to the virial temperature. The normalisation of the density is given by the cosmic baryon fraction.

We experimented with a number of set-ups of three-way mergers between clusters, varying the masses and initial positions of the clusters. Here we present a simple set-up of three clusters that reproduce some of the morphological features observed in 1RXS J0603.3+4214. See Table 1 for a summary of the cluster parameters.

| Simulation | Mass | a/kpc | kT/keV | (x, y, z)/Mpc | (v_x, v_y, v_z)/km s^{-1} |
|-----------|------|-------|--------|--------------|-------------------------|
| 1         | \(5 \times 10^{14}\) | 500   | 3      | (0.65, 1.3, 0) | (0, -750, 0)             |
| 2         | \(5 \times 10^{14}\) | 500   | 3      | (0.65, -1.3, 0) | (0, 750, 0)              |
| 3         | \(3.5 \times 10^{15}\) | 300   | 3      | (1.95, -1.95, 0) | (-1300, 0, 0)            |

and (i) it resembles the Navarro, Frenk, White (NFW) profile in that as \(r \to 0\), \(\rho(r) \propto r^{-1}\) and (ii) the corresponding distribution function can be written in a simple form. The initial velocity distribution of the DM is assumed to be isotropic, i.e. \(\sigma_u = \sigma_\phi\), and the positions and velocities for the DM particles are set up as outlined in Kazantzidis, Zentner & Kravtsov (2006). For the particle positions, a random deviate \(u\) is uniformly sampled in the range \([0, 1]\) and the function \(u = M_{\text{DM}}(r)/M_{\text{DM}}(r_{\text{max}})\) is inverted to give the radius of the particle from the centre of the halo. The distribution function of any steady-state, spherically symmetric system depends on the phase-space coordinates only through the integrals of motion \(E\) and \(L\), where \(E = \psi - \frac{1}{2}v^2\) is the relative energy, \(L = r\psi\) is the angular momentum of a particle (Binney & Tremaine 1987) and \(\psi(r)\) is the relative gravitational potential, and \(v_t\) is the tangential velocity. We initialize particle velocities by choosing \(L = 0\), since cosmological simulations point to low spin parameters for cluster-sized DM haloes (e.g. Gottlöber & Yepes 2007).

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A more detailed sampling of the parameter space only makes sense, once further X-ray and lensing studies have yielded more stringent constraints.

3 RESULTS

First, clusters 1 and 2 that have an initial relative velocity of \(1500\text{ km s}^{-1}\) collide with their cores passing at \(\sim 1.3\text{ Gyr}\) after the start of the simulation. As clusters 1 and 2 collide in a head-on collision, they drive out an ellipsoidal shock front that is strongest along the merger axis. Meanwhile, cluster 3 grazes cluster 2 and loses some of its gas and DM. As it then heads north, it is pulled in along the merger axis. Meanwhile, cluster 3 grazes cluster 2 and

Figure 1. Radio–X-ray overlay of 1RXS J0603.3+4214. The image from the ROSAT All-Sky Survey was smoothed with a 200 arcsec FWHM Gaussian and is shown in orange colours. Solid contours are from the WSRT L-band image and drawn at levels of \([1, 2, 4, 8, \ldots] \times 0.15\text{ mJy beam}^{-1}\) (from van Weeren et al. 2012).

Table 1. Simulation parameters.

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are found in the region around cluster 3. This hot gas drives out a shock that is strongest in the region where the combined shock front forms a region that is straight for $>1$ Mpc at the top-left of Figs 2 and 3. Near the centre of mass as well as south of it, one sees the cold front from the cold gas from the cluster centres that is coincident with the dense plume seen in Fig. 2. They have a more complex morphology than those seen in binary mergers.

Projections of $n^2 \sqrt{T}$ as proxy for the X-ray surface brightness together with the surface mass density are shown in Fig. 3. The shocks are visible as discontinuities in the X-ray surface brightness. The bright cores of clusters 1 and 2 separate after core passage with a bright bridge of stripped gas joining them. Also the DM haloes separate and then finally merge at around 4 Gyr after the start of the simulation. However, the separation between DM and gas (bulleticity) is not nearly as big as in the Bullet cluster, where the relative velocity between the clusters is much higher. We also computed the projected mass within cylindrical bins centred on the centre of mass of the triple system (see inset in Fig. 3, which shows the projected mass at 3.5 Gyr after the start of the simulation). We also notice some X-ray bright plumes that extend slightly along the minor axis of the X-ray emission which appear even more pronounced in the ROSAT image. The simulation predicts still a fair amount of X-ray emission at the core of cluster 3, even after 3.5 Gyr. This is not visible in the ROSAT image. If this absence is confirmed, this might imply that cluster 3 has less gas than assumed here, possibly as a result of stripping from its first encounter or because it has a higher core entropy than assumed here.

The shocks in our simulation are detected using a multidimensional shock detection module adopted from the SPPM code (Anderson & Woodward 1995) based on pressure jumps across the shock. The basic algorithm evaluates the jump in pressure in the direction of compression (determined by looking at the velocity field). If the total velocity divergence is negative and the relative pressure jump across the compression front is larger than some chosen value ($\Delta p/p > 0.25$), then a zone is marked as shocked. The projected energy dissipated in the shock through the central regions of our computational domain is shown in Fig. 4. This may be regarded as a proxy for the energy transferred to cosmic rays, even though the observed radio emission depends on both the cosmic ray spectrum as well as the magnetic fields. The shock strength is highest at the bow of cluster 3 where the Mach number is as high as 4 and the leading edge of the shock forms a fairly straight line. This Mach
number is in line with the Mach number derived from the spectral index of the synchrotron emission, which lies between 3.8 and 4.6 (van Weeren et al. 2012). In accordance with observations, this straight line subtends an angle of roughly 30° with the normal of the major axis of the X-ray emission. This angle depends on the orbit of cluster 3 with respect to the main merger. A velocity of cluster 3 that exceeds the propagation speed of the main merger shock causes this oblique angle. Projection of the shock front leads to a width of the dissipated energy contours of $\sim 200 \text{kpc}$ (Fig. 4). Based on this simulation, the radio halo that fills the region between clusters 1 and 2 does not appear to be directly related to a radio relic (produced by a merger shock) that is seen in projection.

We do not model the radio emission as in van Weeren et al. (2011) as this would merely introduce more unconstrained parameters. From Fig. 4, we would expect a counter relic. The Mach number is high again in the south-east, and one might speculate that the linear structure seen in the radio image in the south-east may be indicative of a shock there. However, the orientation does not quite match what we find in the simulation. While it is impossible to argue for the uniqueness of our reconstruction of this merger, we note that gas clumping as inferred from recent X-ray observations is not able to explain the asymmetry, the angle with respect to the main axis or the straight morphology of the shock front. In summary, our simulations provide evidence that the relic seen in galaxy cluster 1RXS J0603.3+4214 is the result of a triple merger of clusters. Modelling a merger with mass ratio 1:1:0.07 on a trajectory where the smaller clusters skirt the main head-on collision, we can recover (i) the length of the relic, (ii) the shape of the relic and (iii) the angle with respect to the major axis of the X-ray emission. Upcoming multiwavelength data will be used to validate this picture.

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Figure 4. Projection of logarithm of the energy dissipated (in units of erg s$^{-1}$ cm$^{-2}$) at the shock (at 3.5 Gyr).

REFERENCES

Anderson S. E., Woodward P. R., 1995, http://www.lcse.umn.edu
Battaglia N., Pfrommer C., Sievers J. L., Bond J. R., Enßlin T. A., 2009, MNRAS, 393, 1073
Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton Univ. Press, Princeton, NJ
Burns J. O., Roettiger K., Ledlow M., Klypin A., 1994, ApJ, 427, L87
Clowe D., Bradac M., Gonzalez A. H., Markevitch M., Randall S. W., Jones C., Zaritsky D., 2006, ApJ, 648, L109
Colella P., Woodward R. F., 1984, J. Comp. Phys., 54, 174
Ensslin T. A., Biermann P. L., Klein U., Kohle S., 1998, A&A, 332, 395
Fryxell B. et al., 2000, ApJS, 131, 273
Gottlöber S., Yepes G., 2007, ApJ, 664, 117
Hayashi E., White S. D. M., 2006, MNRAS, 370, L38
Hernquist L., 1990, ApJ, 356, 359
Hoeft M., Brüggen M., 2007, MNRAS, 375, 77
Hoeft M., Brüggen M., Yepes G., Gottlöber S., Schwope A., 2008, MNRAS, 391, 1511
Kazantzidis S., Zentner A. R., Kravtsov A. V., 2006, ApJ, 641, 647
Mastropietro C., Burkert A., 2008, MNRAS, 389, 967
Minni F., Jones T. W., Kang H., Ryu D., 2001, ApJ, 562, 233
Pearce F. R., Thomas P. A., Couchman H. M. P., 1994, MNRAS, 268, 953
Pfrommer C., Enßlin T. A., Springel V., 2008, MNRAS, 385, 1211
Poole G. B., Fardal M. A., Babul A., McCarthy I. G., Quinn T., Wadsley J., 2006, MNRAS, 373, 881
Ricker P. M., 1998, ApJ, 496, 670
Ricker P. M., Sarazin C. L., 2001, ApJ, 561, 621
Ritchie B. W., Thomas P. A., 2002, MNRAS, 329, 675
Roettiger K., Flores R., 2000, ApJ, 538, 92
Roettiger K., Burns J., Loken C., 1993, ApJ, 407, L53
Roettiger K., Loken C., Burns J. O., 1997, ApJS, 109, 307
Roettiger K., Stone J. M., Burns J. O., 1999, ApJ, 518, 594
Schindler S., Mueller E., 1993, A&A, 272, 137
Skillman S. W., Hallman E. J., O’Shea B. W., Burns J. O., Smith B. D., Turk M. J., 2011, ApJ, 735, 96
Springel V., Farrar G. R., 2007, MNRAS, 380, 911
Takizawa M., Naito T., 2000, ApJ, 535, 586
van Weeren R. J., Brüggen M., Röttinger H. J. A., Hoeft M., 2011, MNRAS, 418, 230
van Weeren R. J. et al., 2012, A&A, in press
Vazza F., Brüggen M., van Weeren R., Bonafede A., Dolag K., Brunetti G., 2012, MNRAS, 421, 1868
ZuHone J. A., Lamb D. Q., Ricker P. M., 2009, ApJ, 696, 694
ZuHone J. A., Ricker P. M., Lamb D. Q., Karen Yang H.-Y., 2009, ApJ, 699, 1004
ZuHone J. A., 2011, ApJ, 728, 54
ZuHone J. A., Markevitch M., Johnson R. E., 2010, ApJ, 717, 908

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