Cluster merger blast wave and the mystery of ringlike radio-relic formation around some galaxy clusters

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Abstract. In this work I studied the nature and important effects of massive galaxy cluster merger phenomena. Due to inherent complexity of such events analytical solution is impossible, so, numerical simulations are performed using ENZO-2.1 hydrodynamic code. It is noticed that the formation of Mega parsec scale merger shocks in such events substantially change the energy distribution of Inter Cluster Medium. A striking similarity is noticed between expanding intra cluster medium during mergers with the blast wave formation in supernovae explosion. The blast wave meets the void/ accretion shocks when propagated out to the virial radius. Particle acceleration at the meeting point produce a significant amount of synchrotron radio emission through which curved shocks are made visible in radio waves. This study thus also sheds some light on the formation of curved and nearly symmetric radio emission found in Abell 3376, Abell 3667, CIZA J2242.8+5301, plck g287.0+32.9 etc. clusters.

1. Introduction
Remarkable technical development in the field of radio interferometry revealed many spectacular structures in the recent years. Among them the most mysterious are the symmetric Mpc scale radio relics around massive galaxy clusters (e.g. Abell 3667, Abell 3376 etc.) found near or beyond the virial radius (e.g.[1]). Origin of these peripheral ring like radio formation couldn’t be explained properly and remained an outstanding problem for the last decade.

In the hierarchical structure formation framework, clusters are the largest objects in the universe that may have attained virialisation recently, and at present many clusters are still in the process of growing by accretion and mergers. When the mass ratio of the infalling cluster halos in a merger (> 10^{13} M_☉) approaches unity, a gigantic clash takes place. These specific merger events, termed as ‘major mergers’ [6], are among the most energetic events of the universe and energy released in these events may approach 10^{64} ergs.

In a major merger, sudden increase in bulk motion of ICM produces Mpc-scale shock fronts. Strong collisionless shocks are capable of producing high-energy cosmic-ray particles (CR) via diffusive shock acceleration mechanism (DSA; [2]). These curved shocks are also interesting for transforming kinetic energy to turbulent energy by injection of volume-filling turbulence in the ICM [3]. On the other hand, if a turbulent flow is established in the ICM, turbulent dissipation acts on a significantly longer timescale than shocks, and in principle can stochastically re-accelerate the ambient electrons [4] and also amplify magnetic fields by shock compression and dynamo action. Cluster mergers thus greatly affects the energy budget of the ICM and can raise turbulent to thermal energy fraction to as high as 30% ([5], [6] etc.).
2. Simulation of galaxy-cluster mergers

Due to the inherent complexity of the merger events, hydro-dynamical simulations became an important tool for the study of hierarchical assembly of large structures and their evolution. With an aim to understand cluster merger phenomena well, I performed several simulations of major cluster mergers using the ENZO 2.1 hydro-dynamical code [7].

Simulations were performed with the Adaptive Mesh Refinement (AMR), grid-based hybrid (N-body plus hydro-dynamical) code Enzo v. 2.1 [7]. A flat ΛCDM background cosmology with the parameters of the LCDM model, derived from WMAP (5-years data) combined with the distance measurements from the Type Ia supernovae (SN) and the Baryon Acoustic Oscillations (BAO) is used (see [8]). The simulations have been initialized at redshift \( z = 60 \) using the [9] transfer function, and evolved up to \( z = 0 \). An ideal equation of state was used for the gas, with \( \gamma = 5/3 \). Radiative cooling assumed from [10] for a fully ionized gas with metallicity of 0.5 solar.

3. Emergence and evolution of supernova type blast wave

Unlike many previous attempt of controlled binary mergers ([11]) where binary bow type shocks are found, in this realistic cosmic environment simulations a supernovae type blast wave is created after the massive mergers (see Fig 1). Like a blast wave, here, cluster medium pressure expanding supersonically outward from the merging core. This enormous energy comes from the binding energy of new core formation. It has a leading shock front of compressed gases called a merger shock front. It is also noticed that once the shock is emerged, the central dark matter potential has no further control on the evolving shock fronts. Its kinetic energy of wave propagation is not exactly spherically symmetric like most of the blast waves, rather, most of the energy here transferred along the merging axis making it an ellipsoidal shock front [6].

Three panels of the Fig 1 shows the evolution of temperature (pseudo colour) and density (contour) as a time series starting from pre-merger to post merger condition. A clear launch of thermal shock (2nd panel) can be seen after the merger. A ring like formation of shock wave strikingly matches the morphology of a blast wave propagation. So, this is possibly the biggest known blast wave in this universe with a size of > 1 Mpc.

![Figure 1](image.png)

Figure 1. Pseudo colour temperature evolution map with density contours are shown for redshift \( z=0.88, z=0.76 \) and \( z=0.68 \). Slices are cut at the centre of mass with each side of 3 Mpc.

3.1. Expansion of the cluster medium

Cluster merger blast wave after emergence, propagate in to the cluster medium. High pressure that was created due to the release of cluster core binding energy then transferred to the cluster medium through shocks. Materials from the cluster centre then expanded radially outwards...
against the core collapse. In the Fig 2 this process is clearly depicted by velocity vector image. First panel in the figure 2 shows the Pre-merger condition. At this stage two clusters cores are about to merge and the gravitational core collapse and accretion flow is looking dominant force. Materials are falling in to the cluster core which is indicated by the inward vector flow direction. Next panel shows the emergence of a shock and materials started flowing outwards. Velocity vector inside the shock from now turned around radially outwards. Only matter along the filaments are still flowing inside. In the last panel it is clearly seen that a ring like shock front is created and material from the core of the cluster radially pushed towards the virial radius of the cluster. An almost hard surface is created at the shock front where velocity vectors are seen to reverse their direction (See panel 3 Fig 2). This ellipsoidal formation got broken where ever materials are flowing towards the core through filaments.

Figure 2. Same as Fig 1 with density as white contours ($1 \times 10^{-28}$ to $1 \times 10^{-24} \text{gcm}^{-3}$, velocity magnitude in pseudo colour and flow direction as velocity vectors.

3.2. Blast wave energy evolution
Radial variation of total energy of the cluster system is computed. Here total energy means the addition of thermal and the kinetic energy of the cluster medium. Snapshots are taken at

![Figure 3. Panel 1: Radial total energy evolution for each snapshots starting from redshift z=0.82 to z=0.58. Panel 2: Peak energy evolution as points and fitting as line plot](image)

each 0.02 redshift separation and plotted the full evolution of the cluster from redshift z=0.82
upto redshift z=0.58. This cluster merged almost 6.787 Giga year before and blast wave can be traced for more than a Giga year. The radial profile of energy evolution shows almost spheroidal type of energy increment along the radius. It shows an initial increment in the peak energy at the shock front and slowly it looses its energy as goes outwards Fig 3. This profile is exactly similar (with some scaling) to a supernova blast wave. The peak energy falls exponentially to its half of the initial value in about 0.6 Gyr. A curve is best fitted to the peak energy evolution using equation $f(x) = A \exp(-x/t) + B$. The best fit parameters are $A = 7.73 \times 10^{15}$ and $B = 7.5 \times 10^{15}$ with $\chi^2$/DoF value of $6.7 \times 10^{28}$. On the other hand radius of the blast wave roughly seems to increase linearly with the time of its evolution.

4. Discussion

The main finding of this study is that the cluster merger phenomena morphologically and energetically almost similar to the blast waves. This shock when propagated near to or beyond the virial radius of the cluster and interacted with the cluster surroundings (see Fig 1, it took different shape depending on whether it meets the void/ accretion shocks or the filamentary inflow. When it meets the filaments the shock fronts get destroyed and at the surface of interaction the medium becomes turbulent due to Kelvin-Helmhhoz instability and looses the thermal energy and create broken parts on the thermal shock fronts. On the other hand the shock strength is enhanced when it interacted to the accretion shock at the meeting surface of inter-cluster medium and void. This region is thus become the most efficient particle accelerator and magnetic field is magnified due to high compression rate. As a result, these regions produce significant amount of synchrotron radio emission due to acceleration of charge particles in the enhanced magnetic field, and curved shocks are made visible in radio waves. A ringlike formation with several broken bow shocks are thus observed. This study thus tries to connect the cluster merger shock wave and the formation of curved and nearly symmetric radio emission found in Abell 3376, Abell 3667, CIZA J2242.8+5301 etc. clusters.

Approach used here is crude as the code doesn’t include magnetic field and particle acceleration physics. Still the analysis performed on the basis of energy evolution, shock compression and turbulent kinetic energy, provides interesting results in the comparison between these simulations and observations of ring like formations. I believe that even with simplified, purely hydro-dynamical approach I am able to show a first comparison with observed structures.

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References

[1] Joydeep Bagchi, Florence Durret, Gastao B. Lima Neto and Surajit Paul 2006 Science 314 791
[2] Blandford, R., & Eichler, D. 1987, Physics Report 154 1
[3] Subramanian, K., Shukurov, A., & Haugen, N. E. L. 2006, MNRAS, 366, 1437
[4] Brunetti, G., et al., 2007, MNRAS 378 245
[5] Vazza, F., Tormen, G., Cassano, R., Brunetti, G., & Dolag, K. 2006, MNRAS 369 L14
[6] S. Paul, L. Iapichino, F. Miniati, J. Bagchi & K. Mannheim 2011 Astrophysical Journal 726 17
[7] OShea, B. W., Bryan, G., Bordner, J., Norman, M. L., Abel, T., Harkness, R., & Kritsuk, A. 2005a in Plewa T., Linde T., Weirs V.G, eds, Lecture Notes in Computational Science and Engineering Vol. 41 Adaptive Mesh Refinement: Theory and Applications. Springer, Berlin, New York 341
[8] E. Komatsu et al. [WMAP Collaboration], 2009 Astrophys. J. Suppl. 180 330
[9] Eisenstein, D. J., & Hu, W. 1999 Astrophysical Journal 511 5
[10] Sarazin, C., & White, III R.E., 1987 Astrophysical Journal 320 32
[11] Roettiger, K., Burns, J., & Loken, C. 1993 Astrophysical Journal 407 L53