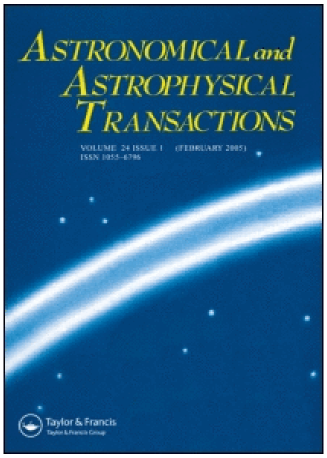


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A. D. Chernin [ab]; G. G. Byrd [c]; M. J. Valtonen [bd]
[a] Sternberg Astronomical Institute, Moscow University, Moscow, Russia
[b] Tuorla Observatory, University of Turku, Turku, Finland
[c] University of Alabama, Tuscaloosa, AL, USA
[d] University of the West Indies, St. Augustine, Trinidad, Trinidad and Tobago

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# SECOND-GENERATION GALAXIES IN MERGING CLUSTERS?

A. D. CHERNIN[a,b,*], G. G. BYRD[c] and M. J. VALTONEN[b,d]

[a]*Sternberg Astronomical Institute, Moscow University, Moscow 119992, Russia*
[b]*Tuorla Observatory, University of Turku, 21500 Turku, Finland*
[c]*University of Alabama, Tuscaloosa, AL 35487, USA*
[d]*University of the West Indies, St. Augustine, Trinidad, Trinidad and Tobago*

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We consider gas-dynamics phenomena in merging clusters of galaxies. According to X-ray observations, merger shocks involve considerable baryonic masses and compress them into large-scale gaseous layers. The internal structure of the layers includes vorticity and magnetic fields generated in the process of the layer formation and evolution. The layers are unstable against fragmentation via thermal instability. The fragments can have baryonic masses, angular momenta and magnetic fields which are typical for galaxies such as the Milky Way. The gravitational condensation of the fragments may lead to the origin of second-generation spiral galaxies in merging clusters. They may differ from the first-generation spirals because they have a higher rate of star formation, a higher luminosity and a bluer colour. Their metallicity must be considerably enhanced which seems to be their major selective feature.

KEYWORDS: second-generation galaxies, merging clusters, gas-dynamics phenomena

## 1 INTRODUCTION

According to the current concepts of galaxy formation, weak perturbations in the primeval mixture of baryons, dark matter and radiation grow with time owing to gravitational instability and give rise eventually to the observed individual galaxies, groups and clusters of galaxies, superclusters and filamentary large-scale structures of the present-day Universe. If dark matter is cold, the process develops in bottom–top manner, so that the first nonlinear perturbations form at relatively small baryonic mass scales of about a million solar masses (which are similar to the masses of globular clusters). These initial cosmic building blocks assemble then into larger haloes with masses from millions to billions of solar masses. Falling in the gravitational potential well of a large halo, baryons form a luminous stellar system in the centre of the potential well. The assembling process proceeds to larger and larger masses via collisions and merging of dark matter haloes that contain stellar systems and intergalactic gas.

Initial stages of the process are observed in the Hubble Deep Field. Small protogalactic blocks look mostly like irregular dwarf galaxies. Ongoing assembling is also observed an various spatial and mass scales. A well-known example of the process on the 1 Mpc scale

* Corresponding author. Email: chernin@sai.msu.ru

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is the mutual motion of the Galaxy and M31 in the Local Group. The giant galaxies with their individual massive dark haloes move towards each other, and their contact collision and merging will occur in the next 5–6 Gyears.

Advanced studies of collisions and merging on the largest scales are seen in rich clusters of galaxies observed in X-ray with CHANDRA and XMM-Newton (see, for instance, Markevitch *et al.* (2002a, b)). It has been recognized that gas dynamics contribute an important role in this process. The formation of extended nonlinear gas-dynamic structures is observed in the intracluster medium. The structures have considerably enhanced density and involve large baryonic masses.

In this paper, we address the gas dynamics of merging clusters or subcluster units and discuss briefly a possible evolution of the nonlinear structures in the intracluster gas. We clarify the physical conditions under which these structures could fragment and produce gaseous protogalaxies. If such processes are really possible, a new generation of galaxies can form within a merging cluster. In this case, galaxy formation would proceed in the up–down manner, contrary to the formation of the first-generation systems.

In Section 2 below, we summarize recent observational data on nonlinear gas-dynamic structures in merging clusters; then in Sections 3 and 4, we discuss vorticity production in the merger shocks and magnetic field generation in the intracluster plasma; it Section 5, thermal instability and layer fragmentation are considered.

## 2 GAS DYNAMICS OF MERGING CLUSTERS

Cosmic shock waves include external accretion shocks as well as merger and flow shocks internal to galaxy clusters (see Cen and Ostriker (1999) and references therein). The cosmic plasma accreting on to the large-scale dark-matter structures (filaments, nearly spherical knots and supercluster sheets) is deflected from the Hubble flow of regular expansion, and it has a typical bulk velocity up to about a few $10^3\,\mathrm{km\,s^{-1}}$ on the spatial scale of approximately 1–3 Mpc. This gas is then shock heated to temperatures ranging from $10^5$ to $10^7$ K in filaments and up to $10^7$–$10^8$ K in clusters and superclusters. Merger shocks are produced during the mergers of clusters or substructure blocks and propagate through the hot intracluster medium. Shocks of various spatial scales form together a complex gas-dynamic structure with Mach numbers of about 1–1000 that can survive for long times inside the medium after the end of the merger owing to the continuous gas inflow through filaments and sheets. Large-scale shocks were also proposed as sites for acceleration of high-energy cosmic rays.

X-ray observations of the largest systems, starting with the Einstein Orbital Observatory, continuing with ROSAT and ASCA and now with CHANDRA and XMM-Newton, have provided a powerful tool for the study of gas dynamics on the cluster scale. The results have confirmed the now prevalent concept that the structure has grown through gravitational amplification of initial weak perturbations and hierarchical clustering. The largest structures, like massive clusters of galaxies, grow, in their final stage, via mergers that may be spectacular phenomenon involving kinetic energy as large as approximately $10^{64}$ erg. These are the most energetic events in nature since the Big Bang. More common are smaller mergers and accretion of material on gaseous overdensities such as filaments or sheets.

The ROSAT image of the cluster A85 shows a relationship between the large-scale structure and cluster merging where small groups are detected infalling along a filament into the main cluster. Supersonic gas dynamics with Mach numbers slightly above 1 are revealed in these processes with sharp gas density discontinuities in the ROSAT images of the clusters A2142 and A3667. CHANDRA and XMM-Newton with high angular resolution provide new insights into gas dynamics on a cluster spatial scale by directly measuring the characteristic velocities of the merger flow, which proves to be 1000–1500 km s$^{-1}$ on a spatial scale of about 1 Mpc. The ASCA observations of the cluster CL0657 (with a red shift of 0.296) demonstrate that this cluster has an extremely high gas temperature of about 17 keV, which makes it the hottest cluster known. The CHANDRA image of this cluster (Markevitch *et al.*, 2002a) shows the classic properties of a supersonic merger.

A clear example of a cluster bow shock was found by CHANDRA in the cluster 1E0657-56 (Markevitch *et al.*, 2002b). This cluster with a red shift of 0.296 was first discovered by the Einstein Observatory as an extended X-ray source. The high-resolution CHANDRA image shows a 'bullet' apparently just exiting the cluster core. The bullet is preceded by an X-ray brightness edge that is the signature of the bow shock. A density jump is found and measured as $3.2 \pm 0.8$ with the use of a detailed temperature map, and the Mach number is estimated as $2.1 \pm 1.1$.

A remarkable pattern of large-scale gas dynamics was recognized by Laine *et al.* (2004) in the Coma cluster, a well-known giant quasispherical cluster of galaxies. Its physics include the double potential well in the cluster central region associated with the two dominant massive member galaxies. This picture is based on the data on galaxy number density distribution as well as on kinematic data and strongly supported by the recent X-ray map of the cluster centre. The moving members of the dominant binary induce via their gravitational potential a powerful gas flow of a complex double helical structure, probably with a cluster-scale shock.

## 3 VORTICITY PRODUCTION IN MERGER STRUCTURES

The formation and propagation of shocks in the intracluster medium are accompanied by secondary gas-dynamic effects, and vorticity production seems to be most natural among them. As is well known, the Kelvin–Helmholtz theorem of vorticity conservation says that eddies neither appear nor disappear in a flow, if, firstly, there is no viscosity in the flow, secondly, the flow is barotropic, thirdly, the acting force is a potential and, fourthly, there are no shocks in the flow. If one of the conditions is violated, vorticity appears with necessity in an initially irrotational gas motion. A general equation that controls the evolution of vorticity was introduced by Friedmann (1934) in his studies of large-scale atmospheric eddies, namely cyclones.

Two principal mechanisms of vorticity production are expected to be most effective under the physical conditions in galaxy clusters and superclusters.

(i) *Scattering of weak hydrodynamic perturbations on a shock front*. The intracluster medium is generally not perfectly uniform, and so shocks propagate in a perturbed density distribution. If perturbations in density (and intracluster velocities as well) are weak in amplitude, one may consider them as superpositions of two fundamental modes; sound waves and entropy waves. Each particular wave interacts with the shock front individually and produces the third fundamental mode, which is a vorticity wave. Analytical treatment of this scattering process has been summarized by Chernin *et al.* (1976) and computer simulation has been reviewed by Chernin (1996). An interesting example is the interaction of a shock front with a spherical gas enhancement ('cloud') in the ambient medium. In this case, the three-dimensional structure of the vortex streamlines looks like the meridianal 'winding' of tori which are concentric around the circle of the vorticity zero velocity. Density enhancements of other shapes produce topologically similar vortex–streamlines structures.

(ii) *Shock–shock collisions*. There may be not only one large-scale shock in a cluster or supercluster when they form via a merger of substructures. In particular, one may imagine two shock fronts which move towards each other and even collide with each other. The initial stages of such a shock–shock interaction are treated by the Courant–Friedrichs (1948) well-known model. Advanced stages of the process need computer simulations which were performed by Voinovich and analysed by Voinovich and Chernin (1995). The vorticity structure produced in this process includes two major annular eddies in the area of the first contact of the shocks. The evolving tangential discontinuities of the Courant–Friedrichs configuration contribute to small-scale vorticity in the same area. Another important contribution is due to the eddy generation on the fronts of the reflected shocks.

Quantitative estimates show that the eddy velocities produced in both cases may typically be $v \approx 10^6$–$10^7\,\mathrm{cm\,s^{-1}}$ on the spatial scales of hundreds of kilopasecs.

## 4 MAGNETIC FIELD GENERATION IN INTRACLUSTER PLASMA

Vorticity on the spatial scales of a hundred kilopasecs in the ionized intracluster medium can generate magnetic fields on the same scales. The most effective mechanism of the field generation seems to be so-called fluctuation dynamo (Zeldovich *et al.*, 1990; Belyanin *et al.*, 1993). The mechanism assumes subsonic chaotic eddy motions and is able to lead to chaotic magnetic fields, if the magnetic Reynolds number is larger than 100. The steady-state rms magnetic field $b$ is presumably given by the balance of magnetic energy and the kinetic energy of the vorticity motions: $b \approx (4\pi\rho v^2)^{1/2}$, where $\rho$ and $v$ are the plasma density and eddy velocity respectively. The mechanism time scale $\tau \approx \lambda/v$, where $\lambda$ is the spatial scale of the process. With $\rho \approx 10^{-27}$–$10^{-26}\,\mathrm{g\,cm^{-3}}$, $v \approx 100\,\mathrm{km\,s^{-1}}$, $\lambda \approx 100\,\mathrm{kpc}$, one has

$$b \approx 0.3 - 3\,\mu\mathrm{G},\ \tau \approx 1\ \text{Gyears}.$$

This field is comparable in amplitude (and mass scale) with the magnetic field of the Galaxy, which is typical for large spiral galaxies. The time rate proves to be less than the time rate of merger process (3–10 Gyears) in clusters and superclusters. It is also instructive that the magnetic fields of such an amplitude are really observed now in intergalactic medium of some rich clusters.

## 5 THERMAL INSTABILITY AND FRAGMENTATION

Large shocked gas layers with internal eddy motions and magnetic fields can be considered as sites where the formation of rotating magnetized protogalaxies may take place. The key mechanism of protogalaxy formation here is thermal instability that may develop in the layers and led to their fragmentation on protogalactic clouds. If the temperature $T$ of a layer is approximately $10^7$ K, and its density $\rho$ is $5 \times 10^{-27}\,\mathrm{g\,cm^{-3}}$, the cooling time via free–free transitions is

$$t_{\mathrm{cool}} = \frac{3.6 \times 10^{11} T^{1/2} m}{\rho_{\mathrm{cl}}} \approx 6\ \text{Gyears},$$

where $m$ is the hydrogen atom mass and the temperature $T$ is measured in kelvins. This means that the layer can indeed be unstable on the merger time scale. The spatial scales of the fragments must meet the Field (1965) criterion

$$\lambda < \lambda_{\mathrm{F}} = u t_{\mathrm{cool}} \approx 6 \times 10^{24}\,\mathrm{cm},$$

where $u$ is the sound speed in the layer. A typical galaxy with the baryonic mass $M_{\mathrm{G}} \approx (10^{10}$–$10^{11})\ M_{\odot}$ collects material from an area of the size $\lambda_{\mathrm{G}} \approx (1$–$2) \times 10^{24}$, which is less than (but near) the critical scale $\lambda_F$. This indicates that the most massive fragments will have typical galactic masses.

The further evolution of protogalactic fragments produced by thermal instability is controlled by their own gravity, the gravity of dark matter within their volume (the dark-matter distribution is more or less uniform on this scale), the magnetic pressure and the centrifugal forces associated with their angular momentum. The combination of these factors having the physical characteristics that we estimated above seem to be favourable for the formation of new galaxies in merging clusters. One may expect that they would be mostly spiral-type galaxies with the angular momentum, per unit mass,

$$S = v\lambda_G \approx 3 \times 10^{30}\,\mathrm{cm^2\,s^{-1}},$$

which is typical for galaxies such as The Milky Way or M31.

In addition, the second-generation galaxies would have a galaxy-scale magnetic field $b_G \approx 3\,\mu G$, which is typical for strong spiral arms. The field might be a result of the amplification (via the gas contraction) of the initially generated frozen-in field $b \approx 0.3\,\mu G$ (see Section 4 and a recent important paper by Petrov *et al.* (2001) on magnetic fields in spirals). In areas with a stronger initial field $b \approx 3\,\mu G$ (see again Section 4), the magnetic pressure could prevent the gas from considerable contraction. It would be interesting to try to observe such strong-field areas in the intracluster medium of merging clusters.

## 6 CONCLUSIONS

To conclude, the large-scale shocks and other nonlinear gas-dynamic structures recently observed in merging or forming clusters of galaxies may be considered as sites of ongoing galaxy formation. The gas-dynamic processes involve considerable baryonic masses that are compressed into large-scale layers. The internal structure of the layers includes vorticity and magnetic fields generated in the process of layer formation and evolution. The layers are unstable against fragmentation via thermal instability. The fragments can have typical galactic baryonic masses, angular momenta and magnetic fields. Their gravitational condensation may proceed in the way described by Eggen *et al.* (1962) and lead to the formation of second-generation galaxies in merging clusters. They may differ from the first-generation spirals because they have a higher rate of star formation and therefore an enhanced luminosity and a bluer colour. Their metallicity must be considerably enhanced, which seems to be their major selective feature. If the second-generation galaxies can really be identified in further special observations, it would mean that the cosmic structure formation proceeds via both clustering and fragmentation, so that the initial bottom–top process is complemented by the top–bottom process at the present epoch.

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