Collision of Merger and Accretion Shocks: Formation of Mpc-scale Contact Discontinuity in the Perseus Cluster

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ABSTRACT

Two Mpc-size contact discontinuities have recently been identified in the XMM-Newton and Suzaku X-ray observations of the outskirts of the Perseus cluster (Walker et al. 2020). These structures have been tentatively interpreted as “sloshing cold fronts”, which are customarily associated with differential motions of the cluster gas perturbed by a merger. In this study we consider an alternative scenario, namely, that the most prominent discontinuity near the cluster virial radius is the result of the collision between the accretion shock and the “runaway” merger shock. We also discuss the possible origin of the second discontinuity at ∼1.2 Mpc.

Key words: galaxies: clusters: individual: Perseus – galaxies: clusters: intracluster medium – hydrodynamics – X-rays: galaxies: clusters

1 INTRODUCTION

The Perseus cluster (A426) is the X-ray brightest cluster in the sky and it has been playing an important role in understanding the processes of active galactic nucleus (AGN) feedback (e.g. Boehringer et al. 1993; Churazov et al. 2000; Fabian et al. 2006; Zhuravleva et al. 2014) and the properties of the hot intracluster medium (ICM, e.g. Hitomi Collaboration 2016) in its core. More recently, the outskirts of the Perseus cluster became a subject of vigorous X-ray observations (e.g. Simionescu et al. 2019). In particular, Walker et al. (2020) have recently reported the discovery of two very extended contact discontinuities (CDs) in the vicinity of the Perseus virial radius. Both of the discontinuities (at r ∼ 1.2 and 1.7 Mpc from NGC 1275) appear in the XMM-Newton and Suzaku data as Mpc-long tangential structures. Walker et al. (2020) suggested that these structures were generated by sloshing activity in the cluster central region some ∼9 Gyr ago.

Generally, there are three most plausible scenarios leading to the formation of CDs in the context of galaxy clusters. In the first scenario, the contact discontinuity (CD) separates the low-entropy gas of the infalling subcluster from the hotter atmosphere of the main cluster (e.g. Vikhlinin et al. 2001). In the second one, differential gas motions in a stratified atmosphere of a perturbed cluster bring gas layers with different entropies to close contact, forming a thin interface (see e.g. Markevitch & Vikhlinin 2007; Zuhone & Roediger 2016 for reviews), usually called a “sloshing cold front”. The third scenario envisages a shock wave crossing another shock (or other discontinuity) and leaving behind a CD. Several versions of this last scenario have already been discussed in Birnboim et al. (2010), Zhang et al. (2019, 2020). In this letter, we will focus on this third scenario, and argue that it can explain the main features of the observed structures in the Perseus cluster.

2 SHOCK-DRIVEN CD FORMATION SCENARIO

The shock-driven scenario of the CD formation in cluster outskirts is illustrated in Fig. 1. A subcluster (dark matter halo filled with gas) moves along the trajectory depicted in the sketch as the black dotted line, and drives a bow shock ahead of it. After the halo passes the core of the main cluster and decelerates, the shock detaches from the subcluster and...
evolves into a runaway shock. Since the gas density profiles in the cluster outskirts are usually steep (approximately \( r^{-3} \) along the non-filamentary directions; see Vikhlinin et al. 2006, and also Zhang et al. 2019 and references therein), the runaway shocks are able to propagate to very large radii while maintaining their strength, and eventually encounter the accretion shocks.

Once the merger shock overtakes the accretion shock, three discontinuities are formed from smaller to larger radii, namely a rarefaction, a contact discontinuity CD, and a forward shock. The forward shock (a.k.a Merger-accelerated Accretion shock, MA-shock) constitutes a new boundary of the cluster atmosphere. This shock has a very high Mach number (approximately equal to the product of the Mach numbers of the runaway and accretion shocks; see the discussions in Birnboim et al. 2010; Zhang et al. 2020), and could travel a large distance – up to a few virial radii into the intercluster medium before it stalls. What remains behind is the rarefaction and the CD. We argue that the outer structure found by Walker et al. 2020 at \( t \approx 1.7 \) Mpc from the cluster center (see their fig. 2) is, in fact, such a CD.

Two facts make this scenario attractive. First, both the runaway and accretion shocks are expected to be broadly tangential to the main cluster radial direction. And, so should be the structures formed in their collision. This is consistent with the geometry of the structure seen in Perseus. Secondly, the accretion shocks are usually located not far from the cluster virial radius (see e.g. Lau et al. 2015; Shi 2016). The CD formed from the shock collision appears at the initial position of the accretion shock and its radial velocity, in the rest frame of the cluster, is relatively small (Zhang et al. 2020). Therefore, the resulting CD naturally fits the properties of the outer structure found in the Perseus cluster.

3 ILLUSTRATIVE SIMULATIONS

Fig. 2 qualitatively illustrates the suggested scenario, using a spherically symmetric 1D numerical experiment. The method and initial conditions for these simulations are described in Zhang et al. (2020). Here, we briefly summarize the key elements of this methodology. The simulations follow the evolution of an idealized 1D self-similar galaxy cluster in a cosmological background (Bertschinger 1985; Shi 2016). An accretion shock arises naturally in these simulations and its radius slowly increases with time. At some moment, a secondary shock with a moderate Mach number is initiated at the cluster center at the cosmic time \( t = 2.5 \) Gyr to mimic (in the adopted 1D geometry) a runaway merger shock driven by an in-falling subcluster. The interaction between the accretion and the “runaway” shocks is well resolved in these simulations.

Fig. 2 shows the typical time evolution of the gas profiles (left panels) in one of our simulations, labeled as “S1T2M23” in Zhang et al. (2020, see their figs. 1 and 2).

While the characteristic mass scale of the simulated halo is significantly smaller than that of the Perseus cluster, the simulation captures the most salient and universal features of the CD formation scenario. The positions of the runaway and accretion shocks at \( t = 2.7 \) Gyr are marked in the top left panel. At \( t \approx 2.8 \) Gyr, the merger shock overtakes the accretion shock. By \( t = 3.5 \) Gyr, the forward shock is more than two times farther away from the cluster center than the CD.

The right panels in Fig. 2 show a representative set of the gas radial profiles at \( t = 3.1 \) Gyr. Apart from the difference in the overall scale (see discussions above), the profiles bear strong similarity with those shown in Walker et al. 2020 (see their fig. 4). In the right panels, the arrows show the rarefaction, the CD, and the MA-shock front in the density profile (cf. Fig. 1). One can see that the shape of the gas profiles around the CD generally shows a good match to the observations. In particular, the CD separates the low- and high-entropy regions on its two sides, whose entropies differ by a factor of \( \sim 4 \). This is a typical value for a CD, if it is formed by a collision of two shocks moving in the same direction and the leading shock has a much higher Mach number (Birnboim et al. 2010). Zhang et al. (2020) suggested that the high-entropy gas shell between the CD and MA-shock front is a characteristic signature of the past shocks’ collision.

We have also revisited the full three-dimensional cosmological simulation analyzed in Zhang et al. (2020, see their section 3), and found that the scenario illustrated in our 1D model generally holds in the more complex situations. But to find an exact match in geometry and morphology of the structures observed in Perseus is obviously difficult in such a simulation of a single, randomly selected galaxy cluster.

Finally, we speculate on the possible origin of the inner cold front seen in Perseus (\( \sim 1.2 \) Mpc from the cluster center) in the scenario described above. One possibility is that it corresponds to the rarefaction formed in the same shocks’ collision as the main CD (see the top right panel in Fig. 2). In observations, Walker et al. (2020) showed that the gas density and temperature jumps, for the outer cold front, are significantly larger than those for the inner one. This is broadly in line with the results seen in our simulations. Another possibility is that the observed inner structure is a fossil CD, formed by an interaction between the accretion shock and the runaway shock driven by a past merger event. Zhang et al. (2020) have shown that the trajectories of MA-shocks depend on their shock strength and the environment of galaxy clusters. It is plausible that multiple runaway merger shocks successively encounter the accretion shock (or MA-shock) in the formation history of a galaxy cluster (see fig. 7 in Zhang et al. 2020). Since the rarefaction corresponds to a steep pressure decrease with radius but the CD does not, accurately measuring the gas-pressure profile, e.g. via the thermal Sunyaev-Zel’dovich effect, is crucial.

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1 See fig. 1 in Zhang et al. (2019) for a numerical experiment illustrating the transformation of a bow shock into a runaway merger shock. A signature of runaway shocks would be the identification of the driving core which could be characterized by a “slingshot” tail (see Sheardown et al. 2019; Lyskova et al. 2019 for examples).

2 Note that the smoothed appearance of the CD is mainly caused by the limited spatial resolution of the simulations (see appendix in Zhang et al. 2020 for more information).
Figure 1. Sketch illustrating an encounter of a runaway merger shock and an accretion shock. The black dotted line depicts the trajectory of the merging subcluster, which crosses the center of the main cluster, reaches apocenter, and then falls back. The merger shock is initially a bow shock ahead of the subcluster. At later times, the shock detaches from the subcluster and propagates “down” the density gradient towards the cluster outskirts. Eventually, the runaway merger shock overtakes the accretion shock, and generates three discontinuities, including a rarefaction, a contact discontinuity (CD), and a forward shock (i.e. MA-shock). The dashed arrows indicate the direction of motion of these structures. The newly found structure (at $\sim 1.7$ Mpc) in the Perseus cluster may correspond to the CD shown in this sketch (see Section 1).

(tSZ) effect, near the inner feature in the Perseus cluster, may help to distinguish these two possibilities.

4 CONCLUSIONS

In this letter, we propose a shock-driven scenario for the formation of the Mpc-size CDs discovered in the outskirts of the Perseus cluster (Walker et al. 2020). In this scenario, these CDs may arise from a collision between the runaway merger shock and the accretion shock (see the sketch in Fig. 1).

The runaway shock is the merger shock, now detached from the subcluster that initially drives it, after the apocentric passage. After the detachment, the runaway shock continues to propagate to the cluster outskirts, and eventually overtakes the accretion shock. Three discontinuities are generated in the collision between the runaway and accretion shocks, including a rarefaction, a CD, and a forward (Merger-accelerated Accretion, MA-) shock. In this scenario, the outer cold front, seen in the Perseus cluster, is explained as the CD formed in the shock collision, whose geometry and radius are both broadly in line with the observations. The MA-shock is expected to be located at even larger radii. Given that the merger shock velocity is obviously supersonic, the time needed for the CD formation is less than the sound crossing time of the cluster, thus alleviating the need for a long (\sim 9 Gyr; see Walker et al. 2020) evolution of the cold front in the sloshing scenario, where characteristic velocities are subsonic. At the same time, the inner edge (at $\sim 1.2$ Mpc) in Perseus could be explained as either the rarefaction formed along with the outer CD or a fossil CD generated in a past shock-collision event. More accurate gas-pressure measurements near this structure (e.g. via the thermal SZ effect) would be helpful to understand its origin.

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Figure 2. Evolution of gas density, temperature, pressure, and entropy profiles in a 1D cosmological simulation (left panels). The runaway and accretion shocks are indicated in the density profile. The discontinuities (i.e., rarefaction, CD, and MA-shock) formed in the shock collision are highlighted in the right panels (at $t = 3.1$ Gyr). The vertical dotted lines mark the positions of the rarefaction and the CD, respectively. This figure illustrates the formation scenario described in Section 2 (cf. Fig. 1), and provides a good analogue to the observations (see Section 3).