Radio tracers of shock waves in the cosmic large-scale-structure

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The detection of a pair of giant radio structures in the galaxy cluster Abell 3376, reported by Bagchi et al. in this issue, provides insight into the dynamics of the ongoing cosmic large-scale-structure formation. The radio structures trace giant Mpc-sized shock waves. These were either caused by a recent merger of galaxy clusters, one of the most energetic events in the present universe, or by accretion shock waves enveloping any cosmological structure. The latter shock waves are theoretically expected but remained undetected so far.

The galaxy distribution in the universe is highly inhomogeneous, with vast cosmic voids embraced by a network of galaxy filaments, and massive galaxy clusters that contain hundreds to thousands of galaxies and reside at the filament's intersections. This very inhomogeneous matter distribution emerged from an extremely smooth initial state, since the cosmic microwave background reveals only baryonic density enhancements of only 10^{-5} additional parts over the mean at the epoch of recombination, 380.000 years after the big bang when the universe became transparent. These initially tiny density enhancements grew drastically during the history of the universe by their mutual gravitational attraction of neighboring matter. Larger and larger structures form still today due to the violent merging of smaller groups and clusters of galaxies. Simultaneously, there is a smoother accretion flow of matter falling onto galaxy clusters out of the dilute inter-galactic medium.

Any gas Gas falling into the potential wells of galaxy clusters has velocities of up to a few thousand km/s. When it collides with the 10^{7-8} Kelvin hot gas within clusters, shock waves form which heat the in-falling gas to similar temperatures. Magnetic fields in the ionized gas may permit a small fraction of the thermal particles to scatter back into the up-stream region of the shock wave and to undergo the energizing shock compression again and again. This so called *Fermi-I* process produces a non-thermal particle distribution with a power-law spectrum in momentum, which easily extends to ultra-relativistic energies. Although these non-thermal particles are small in number compared to the thermal ones, they can contain a significant fraction of the shock dissipated energy.

The efficiency of the Fermi-I process depends sensitively on the shock's Mach number, which is the ratio of the shock velocity to the initial sound speed. Although most of the energy of the cosmic structure formation is dissipated in the centers of galaxy clusters, the shock waves in the outskirts have significantly higher Mach numbers and therefore should be more efficient particle accelerators, as can be seen in Fig. 1 [i]. Especially the accretion shocks convert basically unprocessed and therefore very cold gas, which leads to high Mach numbers.

Electrons, which were accelerated to energies of 10^{4-5} times their rest mass, emit synchrotron radiation into our radio bands due to their gyro-motion in intergalactic magnetic fields of up to micro-Gauss strength. Such radio emission from shock waves in galaxy clusters was observed since the 1970th [ii] and named *cluster radio relics. H*owever, only lately the association with cluster merger shock waves was recognized [iii].

Bagchi et al. interpret the double radio relic in Abell 3376 as the emission from the accretion shock of the cluster. The dual radio morphology may be caused by the stronger matter flow onto the cluster along the embedding galaxy filament. If this interpretation is correct, we would have the first identification of an accretion shock wave. Such shock waves should also accelerate particles to much higher energies than the ones observed in the radio. High energy electrons can scatter photons of the cosmic microwave background into gamma-rays bands and thereby contribute to the observed gamma-ray background [iv]. Accretion shocks may also be the origin of the still mysterious ultra-high-energy cosmics rays [v], which are protons with energies up to 10^{20} eV. Therefore, the radio relics in Abell 3376 mark locations to be monitored for all kinds of high energy radiation.

There is another plausible explanation for the double relics. In the late stage of violent merger of similarly sized galaxy clusters an outgoing pair of shock waves is expected within the volume of the merged cluster. These shock waves steepen, while they run into diluter gas of the cluster outskirts, similar to tsunamis waves running into shallow water. A resulting pair of radio relics was indeed observed in a morphological similar and merging cluster, Abell 3667 [vi], and well reproduced by numerical simulations [vii]. Such a pair of shock waves can also be seen in Fig. 1, roughly 3 Mpc away from the center of the main cluster.

In summary, the radio relics in Abell 3376 provide us with direct insight into

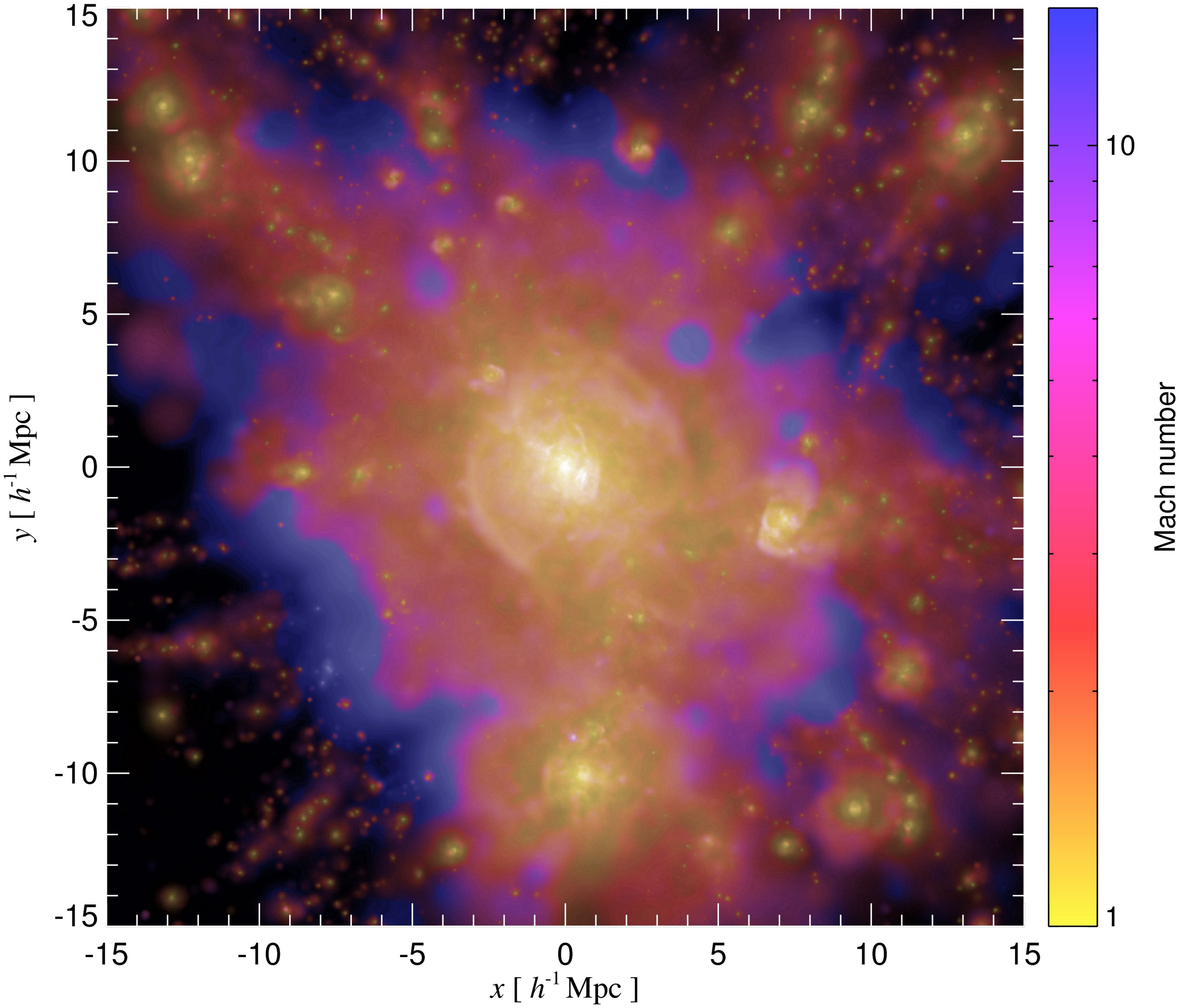

Illustration 1: Energy dissipation by cosmic shock waves around a massive galaxy cluster and two smaller ones. The brightness scales logarithmically with the dissipation rate, the colors indicate the (dissipation weighted) shock Mach numbers. Although most of the energy dissipation occurs within a few Mpc around the cluster centers, the embracing accretion shock waves have the highest Mach numbers (blue structures). Copyright figure courtesy of C. Pfrommer.

the fluid dynamics of cosmic structure formation and a foretaste of the radio glow of the cosmic web [viii], which one hopes to descry with the next generation radio telescopes like the *Low Frequency Array* (LOFAR [ix]), the *Long Wavelength Array* (LWA [x]), and the *Square Kilometer Array* (SKA [xi]).

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