Radio relics: giant magnetic fields in galaxy clusters

by Rainer Beck, Maja Kierdorf, and Sorina Reile

Ordered magnetic fields are observed in radio polarization at the outskirts of several galaxy clusters that extend over megaparsec scales, forming the probably largest magnetic structures in the Universe discovered so far. The two most spectacular examples are called “Sausage” and “Toothbrush”. Effelsberg observations at 4.85 and 8.35 GHz revealed degrees of linear polarization of up to 50%. Recent observations with the Effelsberg telescope with the new Ku-band receiver system (13-15.5 GHz) and with the Sardinia Radio Telescope (SRT) at 18.0-19.2 GHz show that the synchrotron spectra follow almost perfect power laws, as predicted by the theory of diffusive shock acceleration.

Galaxy clusters are among the largest known structures in the Universe, extending over several megaparsecs. They are filled with hot gas, magnetic fields, cosmic rays, dark matter, and many interspersed galaxies. When a galaxy cluster collides with another cluster or an intergalactic gas cloud, a shock forms that compresses gas and magnetic fields and accelerates cosmic-ray particles. As a result, the shocks become visible as huge arc-like features in radio synchrotron emission, called “radio relics”. These were discovered in 1979 with the former 91-m Green Bank Telescope (USA). In more than 70 clusters relics were found so far, but probably many more exist that are too faint to be observed with present-day telescopes. Relics are signs of huge streams of gas that are continuously stirring the structure of the Universe.

Radio waves are ideal to track relics. Shock fronts amplify and order the turbulent magnetic fields of the intracluster medium (ICM), resulting in enhanced radio synchrotron emission with a high degree of linear polarization. At frequencies below about 1 GHz, depolarization due to Faraday rotation in the turbulent ICM significantly reduces the observable polarization degree, so that observations at higher frequencies are advantageous. The excellent polarization performance of the Effelsberg telescope allowed us to measure linearly polarized emission at 4.85 GHz and 8.35 GHz in relics of four galaxy clusters at distances from Earth between about 400 Mpc and 900 Mpc. The two most spectacular cases are the “Sausage” (Fig. 1) and the “Toothbrush” (Fig. 2), named after their appearance. This project was a cooperation between the Thüringer Landessternwarte Tautenburg (TLS), the Argelander-Institut für Radioastronomie an der Universität Bonn (AIfA), and the MPIfR, lead by Maja Kierdorf. The results were published in A&A 600, A18 (2017).

The degrees of polarization of up to 50% in the Sausage and the Toothbrush are exceptionally high, indicating highly ordered magnetic fields, ordered on spatial scales larger than the equivalent beam size of about 350-400 kpc. With linear extents of about 2 Mpc, these relics are among the largest known ordered magnetic structures in the Universe. The lobes of some giant radio galaxies show larger separation, but are not physically connected.

The measured degree of polarization allows us to determine the Mach number, the ratio between the relative velocity of the shock front and the sound velocity. Numbers of larger than two tell us that the clusters collide with velocities of more than 2000 km/s.

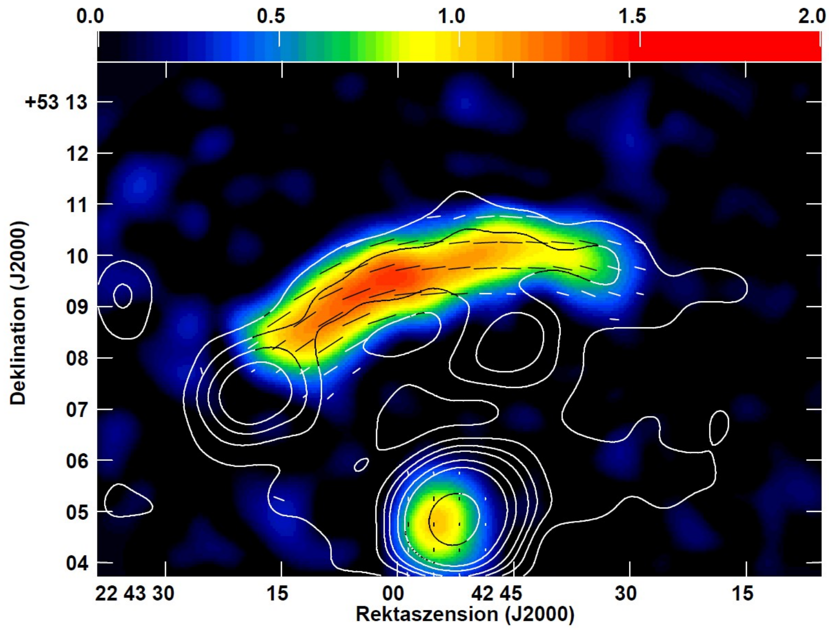

Fig. 1: *The radio relic at the edge of the galaxy cluster CIZA J2242+53, named "Sausage", at a distance of about 800 Mpc. The contour lines show the intensity of the radio emission at 8.35 GHz observed with the Effelsberg telescope, the colors the intensity of the linearly polarized emission (in units of mJy/beam). The lines show the orientation of the ordered magnetic field. The bright source at the bottom of the figure is a radio galaxy that belongs to the same cluster (from Kierdorf et al. 2017).*

Our measurements of the Sausage and Toothbrush relics revealed a rotation of the polarization angles between the two wavelengths, called "Faraday rotation". The rotation angle changes gradually along the axis of the relics, which coherent magnetic fields with a constant direction. Such fields can hardly exist in the relic itself because the turbulent field of a cluster cannot become coherent by compression. We speculate that the Faraday rotation occurs in the intergalactic "cosmic web" in front of the clusters where huge magnetic fields can be even larger than galaxy clusters. The Effelsberg telescope turned out again to be ideal to measure large-scale magnetic fields in the Universe.

One mystery remained about the Sausage and Toothbrush relics. From observations with the interferometric telescopes AMI (at 16 GHz) and CARMA (at 30 GHz) very low integrated flux densities were derived, far below the flux density spectrum extrapolated from the Effelsberg data. This would require a massive spectral break in the energy spectrum of the emitting cosmic-ray electrons, which is in sharp contrast to the well-established theory of diffusive acceleration in shocks. Spectral breaks due to energy losses of the cosmic-ray electrons, as observed in galaxies, can be excluded in relics because of the very low density of thermal electrons and the absence of neutral gas. If true, the breaks would question the shock acceleration theory and call for alternative models. However, our suspicion was that the interferometers were missing most of the extended emission from the relics and hence, the low integrated flux densities measured from the AMI and CARMA data are inaccurate.

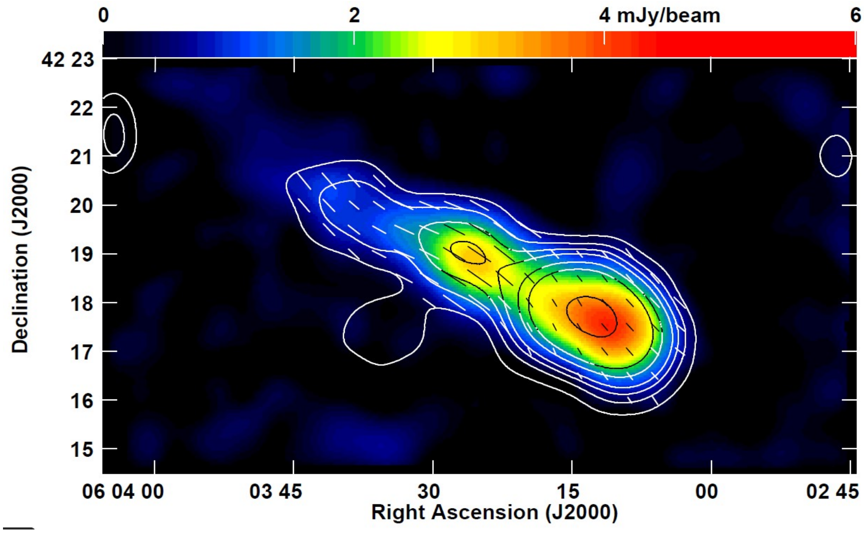

Fig. 2: *The radio relic at the edge of the galaxy cluster 1RXS J0603.3+4214, named "Toothbrush", at a distance of about 900 Mpc. The contour lines show the intensity of the radio emission at 8.35 GHz observed with the Effelsberg telescope, the colors the intensity of the linearly polarized emission (in units of mJy/beam). The lines show the orientation of the ordered magnetic fields (from Kierdorf et al. 2017).*

Single-dish observations at frequencies beyond 10 GHz hold the clue to solve the mystery. Fortunately, the new Ku-band receiver became available in 2019. It operates in two broad bands: 13-15.5 GHz and 15.5-18 GHz. Our proposal to observe the two bright relics was accepted, and observations were performed in December 2019 and January 2020. We spent on-source times of about seven hours for the Sausage and 20 hours for the Toothbrush.

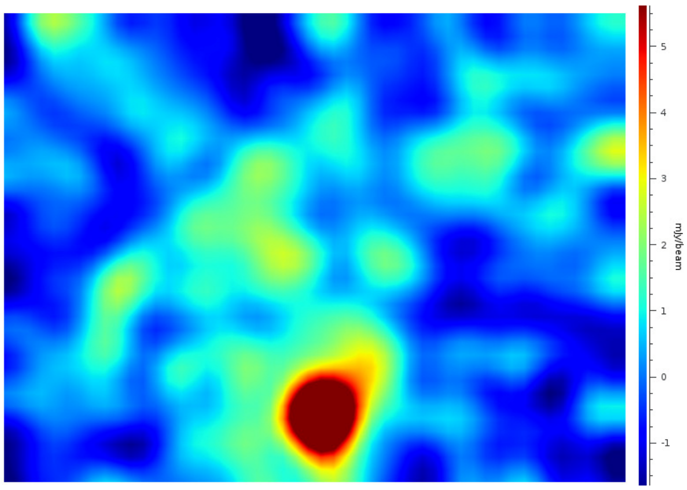

Fig. 3: *The Sausage relic observed with the Effelsberg telescope at 13-15.5 GHz. The colors show the intensity of the total emission (in units of mJy/beam) (published in Loi et al. 2020, arXiv2008.03314).*

One of us (Sorina Reile) worked at MPIfR as an intern in January 2020 and took over most of the data reduction, using the NOD3 system developed by Peter Müller (MPIfR).
For readers not familiar with reducing single-dish mapping, let us briefly describe the procedure. Working with NOD3, every map had to be edited individually. Disturbances were caused by terrestrial radio signals (radio frequency interference, RFI), e.g. by airplanes, could be identified by their strong signal and short duration, and were replaced by dummy values. Disturbances due to clouds extended over larger areas of a map and needed correction by baseline fitting, an option offered by NOD3. After editing, it was still not possible to recognize the relic in a single map.
Since maps scanned vertically and ones scanned horizontally were available, the maps could be combined in a sophisticated way. The tool used for this process is called "Basket Weaving", as it weaves the maps together just like a basket, based on a NOD3 procedure already available within the previous NOD2 package. The final result was a map on which the relics could be identified.
The last step was applying a Gaussian filter onto the map, in order to smear the map gently. This procedure increased the signal-to-noise ratio, so that the relics became prominent. The final maps are shown in Figs. 3 and 4.

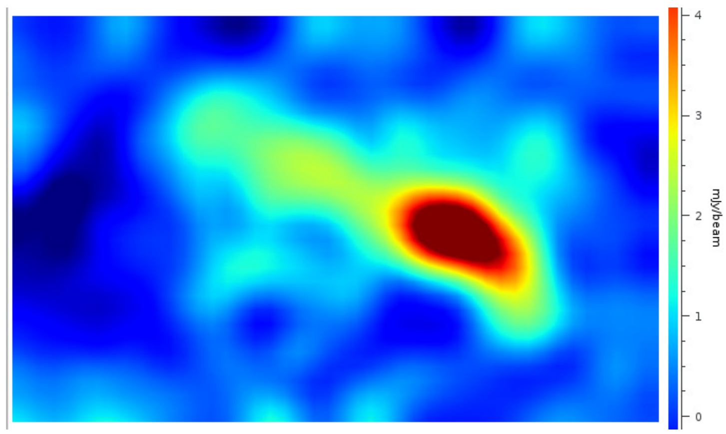

Fig. 4: *The Toothbrush relic observed with the Effelsberg telescope at 13-15.5 GHz. The colors show the intensity of the total emission (in units of mJy/beam) (published in Rajpurohit et al. 2020, arXiv2008.02694).*

Almost simultaneously, a group of radio astronomers observed the two relics with the 64-m Sardinia Radio Telescope (SRT) at 18.0-19.2 GHz and obtained very similar maps. All new maps are shown and discussed in two joint publications. The integrated flux densities from the new maps, combined with the previous ones, clearly indicate that the synchrotron spectra of both relics are straight, with very similar slopes of about -1.15 (Figs. 5 and 6). According to diffusive acceleration theory, such slopes correspond to Mach numbers of about four, in agreement with the high degrees of polarization found from our previous project.

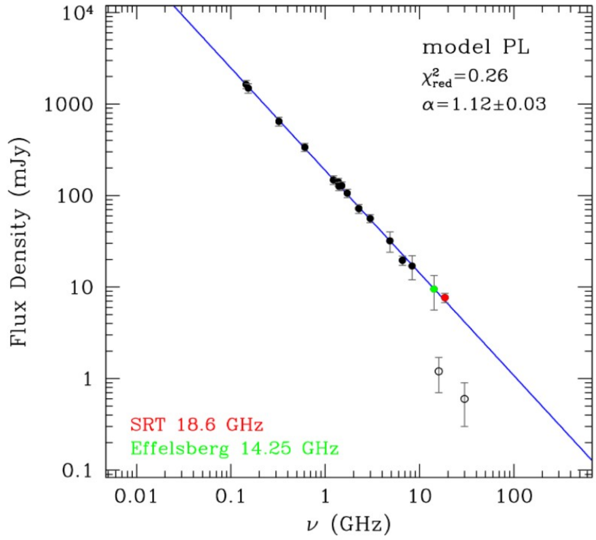

Fig. 5: *Spectrum of the total flux density of the Sausage relic. The slope is -1.12 ± 0.03 (from Loi et al. 2020, arXiv2008.03314).*

We showed that radio relics are a fascinating class of objects that belong to the largest structures known in the Universe. Observations at many radio frequencies allow us to investigate the theory of shock acceleration of cosmic-ray electrons, under almost ideal conditions of the very low gas density. High-frequency observations with single-dish telescopes are crucial for this purpose, in order to fully capture the radio emission. Shocks occur in many astrophysical media, so that our results are of general importance.
In the near future, with the new digital spectro-polarimeter coming into operations, we will also be able to perform polarization observations in the 2cm band.

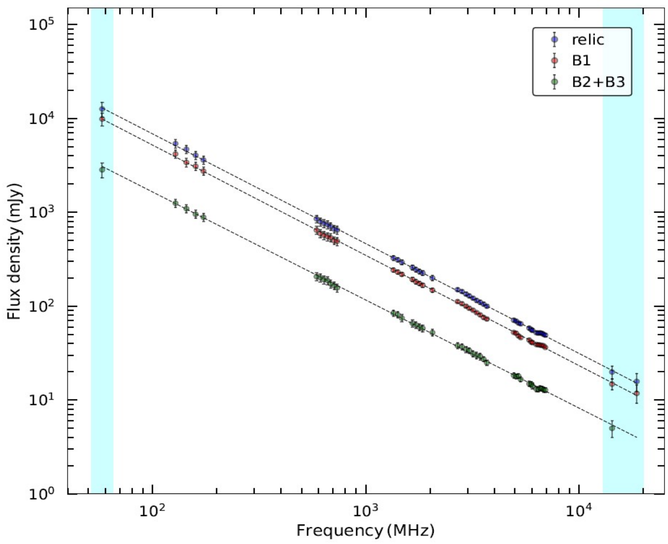

Fig. 6: *Spectrum of the flux density of the Toothbrush relic. The blue points are for the total relic (slope -1.16 ± 0.03), the red points for the brightest western component B1 (slope -1.17 ± 0.03), and the green ones for the middle and eastern components B1+B2 (slope -1.15 ± 0.04) (from Rajpurohit et al. 2020, arXiv2008.02694).*