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RADIO ASTRONOMY

A radio ridge connecting two galaxy clusters in a filament of the cosmic web

F. Govoni[1]*, E. Orrù[2], A. Bonafede[3,4,5], M. Iacobelli[2], R. Paladino[3], F. Vazza[3,4,5], M. Murgia[1], V. Vacca[1], G. Giovannini[3,4], L. Feretti[3], F. Loi[1,4], G. Bernardi[3,6,7], C. Ferrari[8], R. F. Pizzo[2], C. Gheller[9], S. Manti[10], M. Brüggen[5], G. Brunetti[3], R. Cassano[3], F. de Gasperin[5,11], T. A. Enßlin[12,13], M. Hoeft[14], C. Horellou[15], H. Junklewitz[16], H. J. A. Röttgering[11], A. M. M. Scaife[17], T. W. Shimwell[2,11], R. J. van Weeren[11], M. Wise[2,18]

Galaxy clusters are the most massive gravitationally bound structures in the Universe. They grow by accreting smaller structures in a merging process that produces shocks and turbulence in the intracluster gas. We observed a ridge of radio emission connecting the merging galaxy clusters Abell 0399 and Abell 0401 with the Low-Frequency Array (LOFAR) telescope network at 140 megahertz. This emission requires a population of relativistic electrons and a magnetic field located in a filament between the two galaxy clusters. We performed simulations to show that a volume-filling distribution of weak shocks may reaccelerate a preexisting population of relativistic particles, producing emission at radio wavelengths that illuminates the magnetic ridge.

The matter distribution of the Universe is not uniform, but rather forms a cosmic web, with a structure of filaments and galaxy clusters surrounding large voids. Galaxy clusters form at the intersections of the cosmic web filaments and grow by accreting substructures in a merging process, which converts most of the infall kinetic energy into thermal gas energy. A residual fraction of nonthermalized energy is expected to manifest itself in the form of turbulent gas motions, magnetic fields, and relativistic particles. Extended radio sources called radio halos and radio relics are found at the center and the periphery of galaxy clusters, respectively, visible through their emission of synchrotron radiation. Magnetic fields and relativistic particles in the large-scale structure of the Universe can be inferred from observations of these sources.

Observations show that magnetic fields are ubiquitous in galaxy clusters (*1*), whereas radio halos and relics are most common in merging clusters, suggesting that cluster mergers provide the acceleration of relativistic particles necessary for synchrotron emission (*2*). Collisions between nearly equal-mass clusters dissipate large amounts of energy within a few billion years. The merging galaxy clusters Abell 0399 and Abell 0401 are separated by a projected distance of 3 megaparsec (Mpc) and host a double radio halo (*3*). The presence of radio halos at the centers of both Abell 0399 and Abell 0401 was unexpected because radio halos are not common sources, and x-ray (*4*–*7*) and optical data (*8*) suggest that the two systems are still in the initial phase of a merger, before the bulk of kinetic energy of the collision has been dissipated. X-ray data show a hot (temperature $T \simeq 6$ to 7 keV) and nearly isothermal filament of plasma in the region between the two clusters (*7*). There may be a weak shock (Mach number $M < 2$) in the outer part of the filament, at ~650 to 810 kiloparsec (kpc) from the collision axis (equivalent to an angular offset of 8 to 10 arc min). Observations with the Planck spacecraft (*9*, *10*) detected a signal due to the Sunyaev–Zeldovich (SZ) effect, revealing a large-scale filament of gas connecting the two systems. The SZ effect is a spectral distortion caused by inverse Compton scattering of the cosmic microwave background radiation by hot electrons (T ~keV), which is sensitive to the total thermal energy of the intervening medium.

We observed the region between Abell 0399 and Abell 0401 at radio wavelengths to investigate whether relativistic particles and magnetic fields exist on cosmic scales larger than those of galaxy clusters. Using the Low Frequency Array (LOFAR) telescope network at a central frequency ν = 140 MHz (corresponding to a wavelength λ = 2.14 m), we detected a filament of diffuse synchrotron emission connecting the two galaxy clusters.

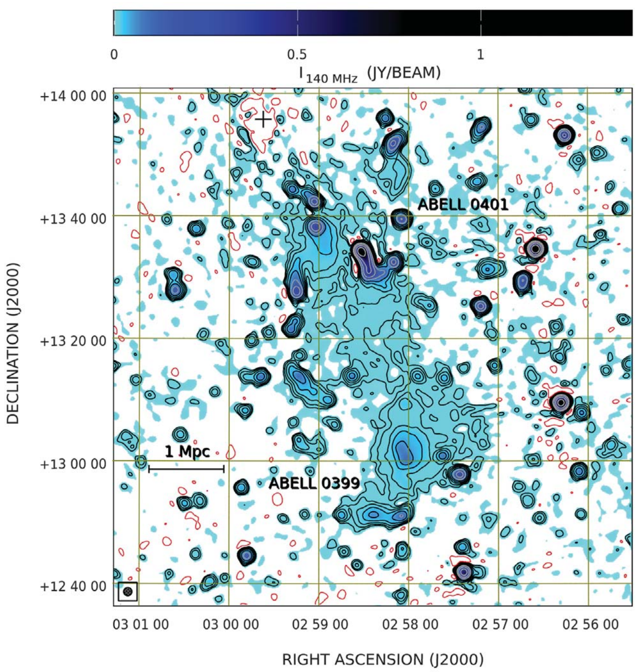

Fig. 1. LOFAR image of the 1.4° × 1.4° region centered on the Abell 0399–Abell 0401 system. Color and contours show the radio emission at 140 MHz with a resolution of 80 arc sec and RMS sensitivity of 1 mJy beam^{-1}. The beam size and shape are indicated by the inset at the bottom left. Contour levels start at 3 mJy beam^{-1} and increase by factors of 2. One negative contour (red) is drawn at −3 mJy beam^{-1}. The black cross (right ascension 02h 59m 38s, declination +13° 54′ 55″, J2000 equinox) indicates the location of a strong radio source that was removed from the image.

[1]Istituto Nazionale di Astrofisica–Osservatorio Astronomico di Cagliari Via della Scienza 5, I09047 Selargius, Italy. [2]ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA, Dwingeloo, Netherlands. [3]Istituto Nazionale di Astrofisica–Istituto di Radioastronomia, Bologna Via Gobetti 101, I40129 Bologna, Italy. [4]Dipartimento di Fisica e Astronomia, Università degli Studi di Bologna, Via Gobetti 93/2, I40129 Bologna, Italy. [5]Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany. [6]Department of Physics and Electronics, Rhodes University, Grahamstown, South Africa. [7]Square Kilometre Array South Africa, 3rd Floor, The Park, Park Road, Pinelands 7405, South Africa. [8]Université Côte d'Azur, Observatoire de la Côte d'Azur, Centre National de la Recherche Scientifique, Laboratoire Lagrange, Blvd. de l'Observatoire, CS 34229, 06304 Nice Cedex 4, France. [9]Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne, 1015 Ecublens, Lausanne, Switzerland. [10]Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy. [11]Leiden University, Rapenburg 70, 2311 EZ Leiden, Netherlands. [12]Max Planck Institut für Astrophysik, Karl-Schwarzschild-Str.1, D-85740 Garching, Germany. [13]Ludwig-Maximilians-Universität München, Geschwister-Scholl-Platz 1, D-80539, München, Germany. [14]Thüringer Landessternwarte, Sternwarte 5, 07778 Tautenburg, Germany. [15]Chalmers University of Technology, Dept. of Space, Earth and Environment, Onsala Space Observatory, SE-439 92 Onsala, Sweden. [16]Argelander Institut für Astronomie, Auf dem Hügel, 71 D-53121 Bonn, Germany. [17]Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester M13 9PL, UK. [18]SRON Netherlands Institute for Space Research Sorbonnelaan 2, 3584 CA Utrecht, Netherlands.
***Corresponding author. Email: federica.govoni@inaf.it**

Figure 1 shows our LOFAR observation of a diffuse radio ridge encompassing Abell 0399 and Abell 0401 at a resolution of 80 arc sec. Our analysis of LOFAR images at higher resolution (figs. S3 and S4) showed that no extended discrete radio sources are present between the two galaxy clusters (*11*). The ridge encompassing Abell 0399–Abell 0401 is not due to the blending of discrete sources, but rather is associated with the cosmic web filament connecting the two clusters (*11*).

To measure the physical parameters of the ridge encompassing Abell 0399–Abell 0401, we masked the regions occupied by the radio halos and other radio sources not connected to the ridge emission (*11*). Figure 2A shows the radio ridge after the masking. It extends between the two cluster cores with a sky-projected length of 3 Mpc. We extracted the brightness profile of the ridge (Fig. 2B) by computing the average brightness in strips of length 3 Mpc and width 0.108 Mpc (one beam width). We modeled the brightness profile using a Gaussian model characterized by three free parameters: the peak brightness, peak position, and full width at half maximum (FWHM). The ridge emission peaks at ~3.7 milliJansky (mJy) per beam with a FWHM of 1.3 Mpc. The ridge is offset to the northwest by 0.16 Mpc from the line connecting the cores of Abell 0399 and Abell 0401.

The flux density of the ridge was calculated by integrating the surface brightness over an area of 3×1.3 Mpc^2 after excluding the masked regions. The average surface brightness at 140 MHz is $<I>_{140\mathrm{MHz}} = 2.75 \pm 0.08$ mJy beam^{-1} (or 0.38 μJy arc sec^{-2}). Taking into account the masked regions, the effective number of instrument beams covering the ridge emission, $N_{\mathrm{eff}} = 160$, is fewer than the 299 beams contained by this area. Assuming that the ridge is present everywhere, even in the masked regions, we extrapolated the total flux density $S_{140\mathrm{MHz}} = <I>_{140\mathrm{MHz}} \times 299 = 822 \pm 24$ (±123) mJy. The uncertainties are the 1σ root mean square (RMS) statistical uncertainty and a 15% systematic uncertainty (indicated in parentheses), to account for the uncertain calibration of the LOFAR flux scale (*12*). This flux density corresponds to a radio power $L_{140\mathrm{MHz}} = 1.0 \times 10^{25}$ W Hz^{-1}. By assuming that the ridge occupies a cylindrical volume, we estimate a mean radio emissivity $<J>_{140\mathrm{MHz}} = 8.6 \times 10^{-43}$ erg s^{-1} Hz^{-1} cm^{-3}.

It is not possible to reliably determine the spectral index of the ridge emission because the available data at 1.4 GHz (*3*) were obtained on different baselines. However, by adopting the spectral index $\alpha = 1.3$ (where $S_\nu \propto \nu^{-\alpha}$) typically found in radio halos (*13*), the mean radio emissivity extrapolated to 1.4 GHz would be $<J>_{1.4\mathrm{GHz}} \simeq 4.3 \times 10^{-44}$ erg s^{-1} Hz^{-1} cm^{-3}. We compared this value with published distributions of emissivities at 1.4 GHz for candidate large-scale filaments (*14*) and with radio halos observed at the center of galaxy clusters (*13*, *15*). The histogram of the emissivity of the candidate filaments and of the radio halos (fig. S2) has two distinct populations with only a partial overlap. The filament in Abell 0399–Abell 0401 is located in the weakest tail of the emissivity distribution of the candidate filaments and is almost two orders of magnitude lower than the typical emissivity of radio halos observed at the center of galaxy clusters.

Figure 3 shows the LOFAR image overlaid on the Planck SZ image, where the SZ effect is quantified with the y parameter ($y \propto \int n_e T \, dl$). The radio ridge is located along the filament of gas connecting Abell 0399 and Abell 0401 detected with Planck (*9*, *10*). There are hints that the radio emission is not homogeneously distributed, e.g., there are some brighter elongated features that align with the filament direction.

The radio ridge encompassing Abell 0399–Abell 0401 has unusual properties. Evidence of large-scale shocks in the accretion flows of intergalactic gas has been found in the merging system ZwCl 2341.1+0000 (*16*), whose diffuse radio emission corresponds with an elongated merging cluster of galaxies. The pair of galaxy clusters Abell 0399–Abell 0401 is at an earlier evolutionary stage, before that of ZwCl 2341.1+0000 (*17*). Radio emission associated with the cosmic web joining Abell 0399 and Abell 0401 indicates that some of the merger energy is converted into nonthermal emission, likely through the acceleration

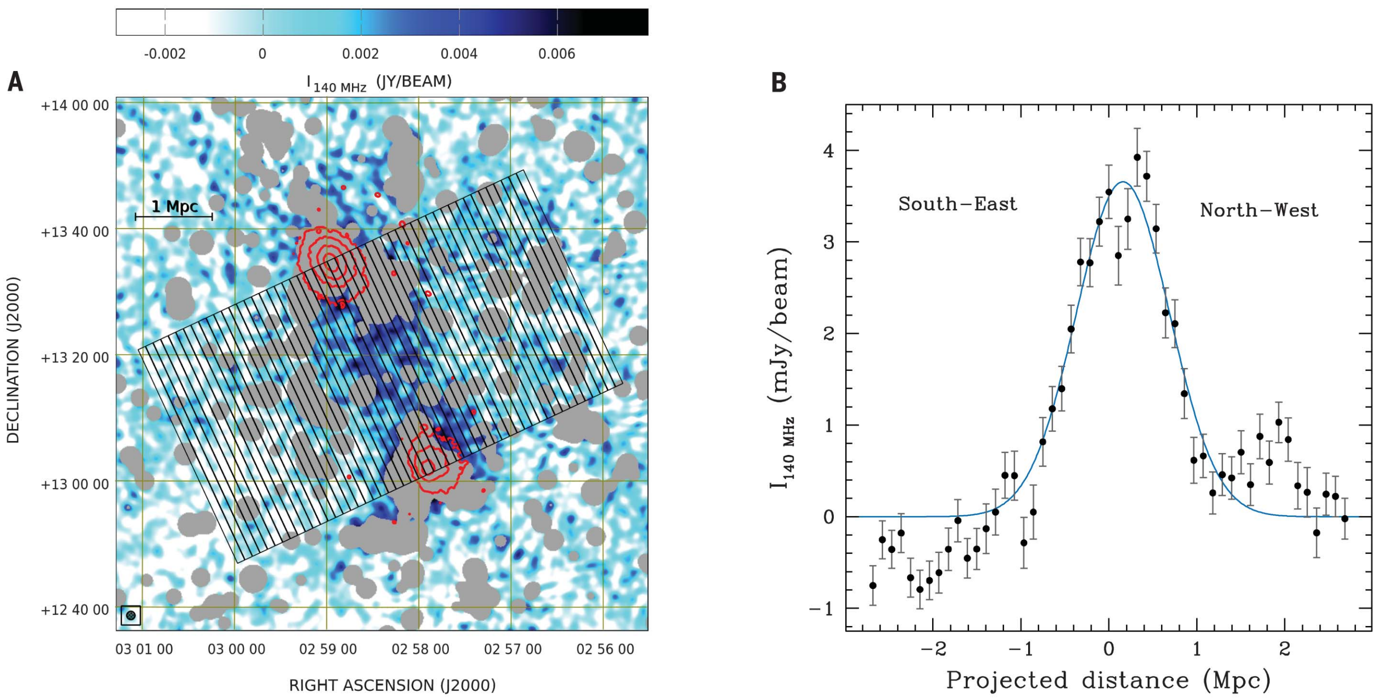

Fig. 2. Brightness profile of the radio ridge. (**A**) Strips used to measure the ridge brightness profile. The x-ray emission (*3*) from Abell 0399 and Abell 0401 is overlaid in red contours. The color bar represents the LOFAR image in Fig. 1 after masking of sources not related to the radio ridge (gray areas). The width of the strips is 0.108 Mpc (one beam width) and their length is 3 Mpc. The strips are inclined 25° east of the vertical axis and a reference point (at right ascension 02h 58m 26s, declination +13° 18′ 17″, J2000 equinox), which is located halfway along the line connecting the x-ray positions of Abell 0399 and Abell 0401. (**B**) Brightness profile of the ridge emission extracted by measuring the average surface brightness in each strip. The error bars indicate $\sigma/\sqrt{N_{\mathrm{eff}}}$, where σ is the image noise rms and N_{eff} is the number of independent beams in each box, excluding the masked areas. The line represents the best-fitting Gaussian model.

of electrons by shock waves and turbulent motions before the collision of the galaxy clusters.

If we assume that the relation between thermal gas density and magnetic field strength found in galaxy clusters (*18*) is also valid in the ridge connecting Abell 0399–Abell 0401, then the thermal gas density of 3×10^{-4} cm^{-3} found in the ridge (*7*) would correspond to a magnetic field strength $B < 1$ μG. Because of energy lost to synchrotron and inverse Compton radiation, the lifetime for relativistic electrons emitting at 140 MHz is ≤230 million years. The maximum distance that these relativistic electrons can travel in their lifetime is ≤0.1 Mpc (*2*), more than an order of magnitude smaller than the size of the ridge. There must be a mechanism that reaccelerates and/or injects the electrons in situ throughout the ridge.

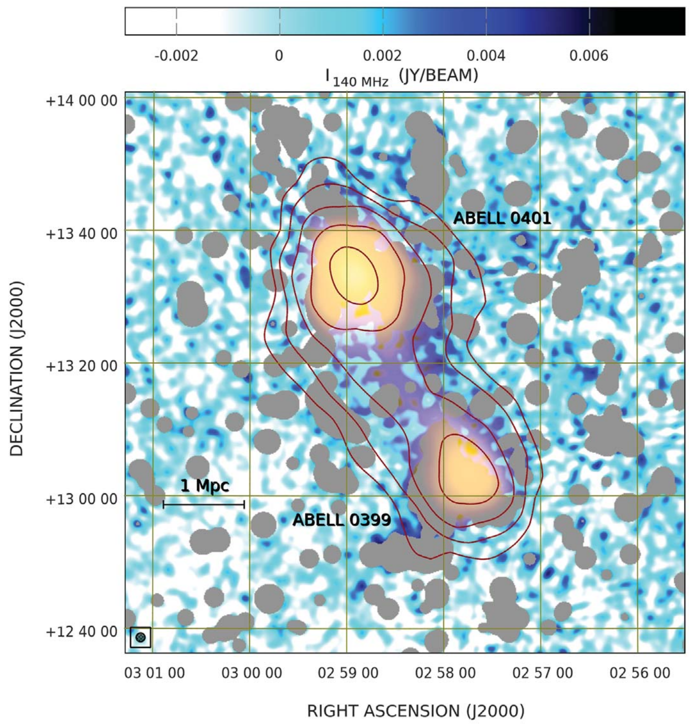

Fig. 3. Composite image showing radio and SZ emission around Abell 0399–Abell 0401 detected by the Planck satellite. The same LOFAR image as in Fig. 2 was overlaid with the Planck *y*-parameter image in yellow tones and brown contours. The Planck data show a bridge of gas between the pair of galaxy clusters Abell 0399–Abell 0401 in the same location as the LOFAR ridge. Contour levels start at 10^{-5} and increase by factors of $\sqrt{2}$.

The accretion of matter on large scales along the Abell 0399–Abell 0401 filament likely injects shock waves and turbulent motion on a wide range of spatial scales. As in the case of radio relics, diffusive shock (Fermi-I) acceleration (DSA) or reacceleration may power radio-emitting electrons and explain this large radio ridge. However, it is difficult to account for such strong emission from shocks before the collision between Abell 0399 and Abell 0401. We explored this scenario using magneto-hydrodynamical simulations with the Enzo code (*19*). Our simulations evolved a pair of merging galaxy clusters at a resolution of 3.95 kpc, with final masses and resultant proximity similar to the Abell 0399–Abell 0401 complex (*11*). To quantify the expected radio emission, we combined the electrons freshly accelerated at shock waves in the simulation with a radio-emission model, which has been used previously to model radio relics (*20*–*22*).

Figure 4 shows the projected gas density in the simulation after rotating the system to resemble the observed SZ morphology of the Abell 0399–Abell 0401 complex. Radio emission by freshly accelerated electrons falls ~1000 times below the sensitivity of our LOFAR observation

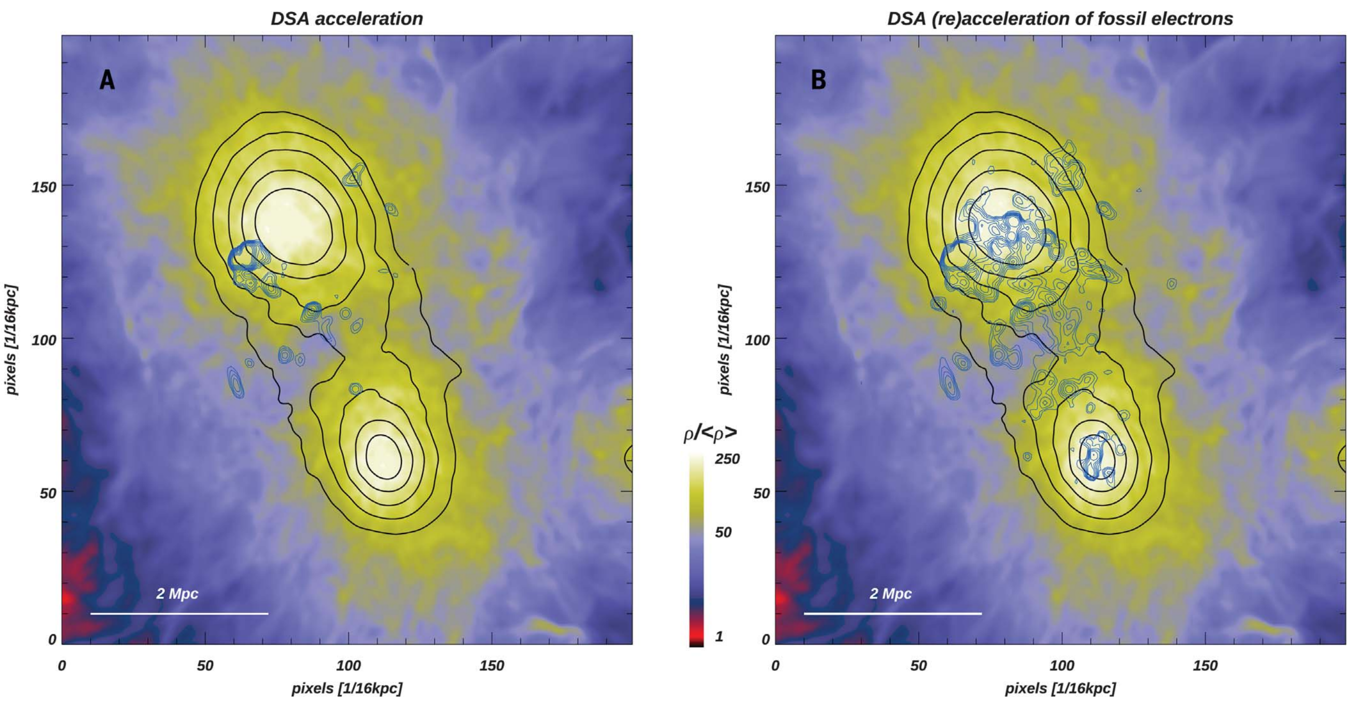

Fig. 4. Volume rendering of the projected gas density (colors), integrated SZ signal (black contours), and radio emission (blue contours) for our simulated pair of interacting clusters (*11*), oriented to resemble the Abell 0399–Abell 0401 pair. Blue contours show the simulated detectable radio emission (≥ 3σ RMS of our LOFAR observation) at 140 MHz, for freshly accelerated electrons (**A**) and with an additional contribution of reaccelerated electrons (**B**). Only the system in (B) resembles the real observation. Movie S1 shows an animated version of this figure.

(Fig. 4A), owing to the scarcity of strong shocks in this region (which is filled by a ~5×10^7 K plasma, heated by gas compression), and to the drop of the assumed electron acceleration efficiency for $M \leq 3$ shocks (*23*). This generates a patchy emission that traces the location of the strongest shocks. In this scenario, the only emission detectable by our LOFAR observation would be associated with a substructure transiting transverse to the line of sight (traced by a weak, M ~3 to 4 shock similar to region "d" in fig. S3). Our LOFAR observation shows emission that is brighter and more broadly distributed across the ridge.

As an alternative model, we tested the additional contribution from a preexisting population of relativistic electrons, reaccelerated by shocks in the region (Fig. 4B). This is a viable mechanism to illuminate the radio ridge only if the preexisting electrons that are reaccelerated by shocks with M ~2 to 3 are accumulated at a Lorentz factor $\gamma \geq 10^3$ and filling most of the ridge volume. This limits the age of these electrons to <1 billion years due to radiative losses. Circumventing this time constraint would require unidentified volume-filling reacceleration mechanisms in such dilute plasmas.

The nonthermal diffuse emission observed in the Abell 0399–Abell 0401 system extends far beyond the boundaries of the two radio halos and fills a region in their outskirts that is still dynamically evolving. We interpret this as evidence of intergalactic magnetic fields connecting two galaxy clusters and of spatially distributed particle reacceleration mechanisms in these regions.

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/364/6444/981/suppl/DC1
Materials and Methods
Figs. S1 to S7
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A radio ridge between two galaxy clusters

Galaxy clusters contain dozens or hundreds of galaxies, vast quantities of hot gas, and large amounts of dark matter. The gas can emit at radio wavelengths if it contains electrons at relativistic speeds, which can be injected by active galaxies or accelerated during a merger between two clusters. Govoni *et al.* used the Low-Frequency Array (LOFAR) radio telescope to observe a ridge of radio-emitting plasma extending between two galaxy clusters that are approaching a merger. The results imply that intergalactic magnetic fields connect the two clusters and challenge theories of particle acceleration in the intergalactic medium.

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