Radio emission confirms that a magnetic field spans intergalactic space

The Low Frequency Array telescope detected previously unobserved synchrotron radiation between two merging galaxy clusters.

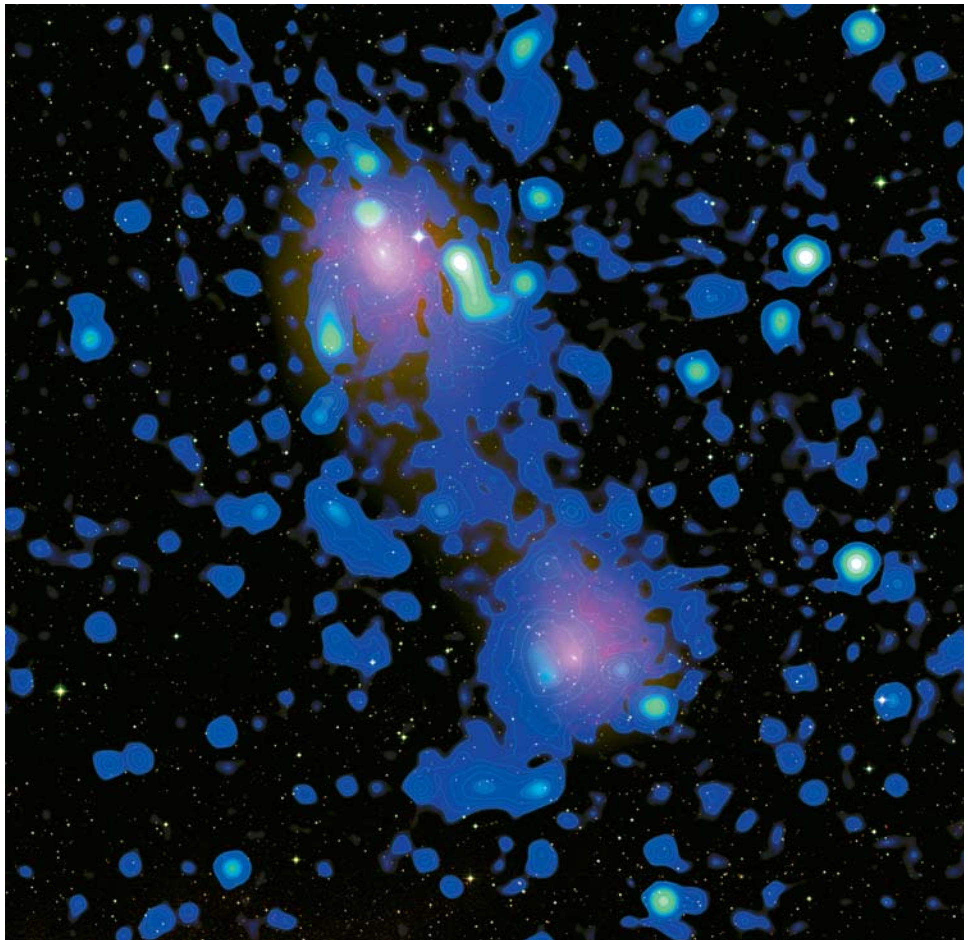

FIGURE 1. A FILAMENTARY STRUCTURE joins the merging galaxy clusters Abell 0399 and Abell 0401. The cluster positions are illuminated by x-ray observations (pink) collected by the European Space Agency's (ESA's) *XMM-Newton* observatory. The faint yellow around and between the clusters shows the filamentary structure inferred from microwave photon-intensity measurements collected by the ESA's *Planck* satellite. The radio synchrotron emission (blue) detected using the Low Frequency Array telescope provides the first evidence for a previously unseen 3-megaparsec-long magnetic field connecting the clusters. (Image by M. Murgia, INAF.)

Think of the large-scale universe as a web: Filamentary structures—threads of galaxies, gas, and dark matter—crisscross space. Where they intersect, gravitationally collapsing material forms galaxy clusters that can then merge through some still-unknown process. Some of the energy released by cluster mergers helps power relativistic particles that spiral around magnetic field lines.

One way that astronomers observe what happens during a merger is by detecting emissions that come from superheated plasma known as the intracluster medium (ICM). The density of the ICM is so low that the only way for matter to interact is through collisionless dealings between the plasma's electric and magnetic fields. X rays are emitted from the interaction of the plasma's electric field with free electrons; synchrotron radiation is emitted from cosmic-ray particles traveling through magnetic fields. (See the article by Lawrence Rudnick, PHYSICS TODAY, January 2019, page 46.)

Astronomers have long wondered whether the radio emission from magnetic fields in clusters extends to the filamentary structures, which contain about half of the universe's baryons. The detection of emission there would be a first step toward understanding the physical processes that affect those baryons, and it would confirm the cosmic web structure of the universe.

The effort to find emission associated with filamentary structures has come up short so far, although the presence of filaments has been inferred from the detection of UV absorption lines (see PHYSICS TODAY, July 2008, page 12). Radio sources extending beyond the ICM of galaxy clusters haven't been detected by low-frequency radio telescopes because of insufficient sensitivity and calibration difficulties. Searches in the soft-x-ray spectrum await more sensitive satellite observations.

Now radio synchrotron emission has been newly detected between two merging galaxy clusters by the Low Frequency Array (LOFAR) telescope. It was built and designed and is operated by the Netherlands Institute for Radio Astronomy with contributions from international partners. A collaboration led by Federica Govoni of Italy's National Institute for Astrophysics has found that the synchrotron emission arises from a magnetic field that extends over distances greater than previously thought possible.[1]

A European-sized radio dish

Measurements made before the new LOFAR observations led Govoni and her colleagues to suspect that a filamentary structure exists between the merging galaxy clusters Abell 0399 and Abell 0401. Figure 1 shows the clusters' x-ray emission collected by the European Space Agency's (ESA's) *XMM-Newton* observatory. Microwave photon-intensity measurements around and between the clusters can help unravel their history and were collected by ESA's *Planck* satellite

FIGURE 2. THE LOW FREQUENCY ARRAY (LOFAR) TELESCOPE is a collection of 25 000 individual dipole antennas distributed among 51 stations across Europe. One of the densely spaced Dutch stations is shown here. Each antenna in the center group—a metal pole with wire mesh underneath—detects low-band frequencies in the range of 10–80 MHz. The other antenna groups are housed in aluminum tile boxes and detect high-band frequencies in the range of 120–240 MHz. (Photo by © Top-Foto, Assen.)

(see PHYSICS TODAY, June 2015, page 20). But without detecting radio emissions, astronomers couldn't conclusively say whether a filamentary structure and magnetic field existed between the two clusters.

LOFAR was designed to detect ultralow-frequency radio emissions in the range of 10–250 MHz (see PHYSICS TODAY, March 2011, page 24). The telescope uses 25 000 electronically linked, digital dipole antennas in stations spread across France, Germany, Ireland, Italy, Latvia, the Netherlands, Poland, Sweden, and the UK. Each antenna is essentially a metal pole in the ground with some mesh wire underneath it. That design "was very cost efficient and that's one of the greatest attributes of LOFAR," says Amanda Wilber, a LOFAR astronomer from the University of Hamburg in Germany not involved with Govoni's research.

Individual antennas far from each other create a long baseline that enables LOFAR to detect the faint radio energy emitted by distant planets, stars, galaxies, and clusters. Such a baseline can be used to produce sharp, highly resolved images. In the Netherlands, the antennas are spaced closely together, which provides an extended picture of the sky. The Dutch stations of the LOFAR array, one of which can be seen in figure 2, provided Govoni and her colleagues with sufficient resolution and sensitivity to detect the broad radio emission coming from the extended magnetic field.

Before the researchers could make the successful detection, they had to synchronize and calibrate all the antennas. "It's one of the most challenging parts for not only LOFAR but [all] low-frequency radio observations," says x-ray astronomer Hiroki Akamatsu of the Netherlands Institute for Space Research. Charged particles in Earth's ionosphere emit energy at frequencies that interfere with radio-astronomy telescopes. But in 2016 a team led by Reinout van Weeren of Leiden University in the Netherlands developed an effective calibration method for the LOFAR telescope that entails modeling the ionosphere and then removing its contribution from the radio-emission observations.[2]

With the new calibration, the LOFAR community "can basically limit the effects of the ionosphere and see what is really happening above the atmosphere of the Earth," says Wilber. "We made a lot of progress, and now we have very reliable results."

The new LOFAR findings, the 140 MHz synchrotron emission shown in figure 1, provide clear evidence for the previously unseen magnetic field. Astronomers have observed radio relic emissions, which originate from individual galaxies and galaxy clusters. But the LOFAR detection is the first to observe the emission connecting two distant clusters. The magnetic field extends 3 megaparsecs (about 10 million light-years) from the clusters, far enough that the emission cannot be mistaken for a radio relic. Using similar magnetic field properties of already identified clusters, Govoni and her team estimate that the field strength is less than 1 μG, or about one-millionth the strength of Earth's magnetic field.

Shocks to the system

Electrons in the magnetic field lose energy to synchrotron radiation and inverse Compton scattering over time. First-order calculations suggest that the electrons in the filament can therefore only travel at relativistic speed for 230 million years. At that rate, the maximum distance they could travel would be 0.1 Mpc, about one order of magnitude less than the length of the observed radio bridge. To get across the filament and its magnetic field, some mechanism acting along the entire cosmic-sized filament must accelerate the relativistic electrons to give them an extra boost.

To identify such a mechanism, one of Govoni's coauthors, Franco Vazza of the University of Bologna in Italy, performed magnetohydrodynamic numerical simulations.[3] In the model, the particles in the filamentary structure are energized by shock waves produced from merging clusters. The first simulation accelerated a population of relatively young electrons to not-quite-relativistic speed for 230 million years. But the associated radio emission was about one-thousandth as intense as the LOFAR observations.

Electrons need a GeV of energy to radiate detectable synchrotron emission at radio frequencies. The shock waves were too small and inefficient to get the job done in the first simulation. The second one reasonably reproduced the LOFAR intensities by including an additional, preexisting population of billion-year-old relativistic electrons that get accelerated by stronger merger-induced shock waves.

Several details about the mechanism still need to be worked out. Govoni and her colleagues do not know yet where the old relativistic electrons come from nor what mechanism fills the filament with them. "It is important to understand whether the emission detected in the filament that connects Abell 0399 and Abell 0401 is a common phenomenon in the cosmic web," says Govoni. "I hope that astronomers will soon find other magnetized filaments."

Alex Lopatka

References

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2. R. J. van Weeren et al., *Astrophys. J., Suppl. Ser.* **223**, 2 (2016).
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A big step for nanoporous graphene provides a small step for desalination

Carbon-nanotube reinforcement and template-based etching help scale up membranes.

Residents of Cape Town, South Africa, planned their daily lives around a quota of 50 liters of water per person per day during the first months of 2018. As the city's freshwater reservoirs dwindled, the municipal government rushed to bring a desalination plant on line. Fortunately, heavy rains in June ended the region's three-year drought. But the city's water crisis illustrated a situation that's becoming increasingly common in the face of growing populations and changing climate. The United Nations predicts that two-thirds of the world's population will face freshwater shortages by 2025.

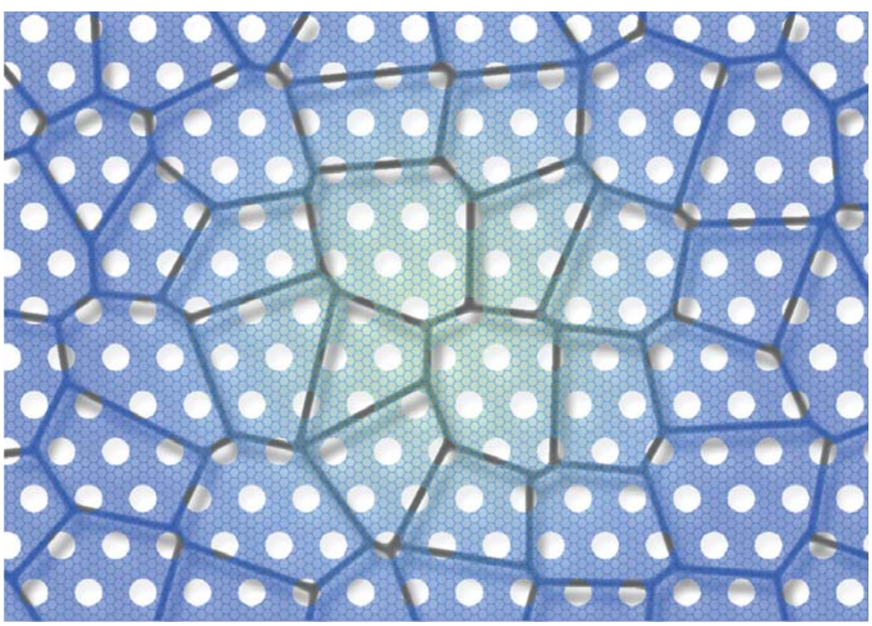

FIGURE 1. NANOPOROUS SINGLE-LAYER GRAPHENE is reinforced by a network of carbon nanotubes. The nanotubes create microscale sections, represented by the outlined polygons, that ensure the membrane's structural integrity. (Adapted from ref. 1.)

The planet's water is 97% seawater, which could in principle provide a steady freshwater supply. The first desalination plants were built in the 1960s, and now 20 000 facilities furnish water to 300 million people globally. Saudi Arabia produces 20% of the world's desalinated water and, along with the United Arab Emirates and Kuwait, relies on desalination for daily life. Israel meets more than half of its domestic needs with Mediterranean seawater, and desalination provides a third of Melbourne, Australia's municipal water supply. (See PHYSICS TODAY, June 2016, page 24.) The US Geological Survey estimates that the average American uses nearly 400 L of water per day. (The average water footprint per capita, which accounts for all goods and services consumed, is nearly 8000 L per day in the US.)

The original desalination plants were based on evaporating and then condensing seawater. Since 2005, however, most new plants have relied on reverse osmosis, and that method now accounts for 50% of the world's desalination capacity. In reverse osmosis, hydrostatic pressure forces saline water through a semipermeable membrane. Dissolved salts are blocked so that fresh water ends up on the other side. Reverse osmosis is the most energy-efficient desalination technology on the market. (See the Quick Study by Greg Thiel, PHYSICS TODAY, June 2015, page 66.)

Reverse osmosis, however, still suffers from poor freshwater recovery rates and high cost due to energy use. Some 40% of seawater and 80% of brackish groundwater can be recovered commercially as freshwater. The by-product is a briny concentrate. The plants require 3–10 kWh of electricity to produce 1000 L of fresh water. That's the energy equivalent of running an electric clothes dryer several times. Most of that energy is used to move saltwater through the membrane.

Research into reducing that energy focuses on improving membrane efficiency and durability. An ideal membrane should be thin to maximize water permeability, selective to isolate particles and solutes, and mechanically robust to avoid breakage and leakage. It also needs to be meters in size for use in commercial desalination. Today's reverse-osmosis