LETTERS

A low-frequency radio halo associated with a cluster of galaxies

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Clusters of galaxies are the largest gravitationally bound objects in the Universe, containing about 10^{15} solar masses of hot (10^8 K) gas, galaxies and dark matter in a typical volume of 10 Mpc^3. Magnetic fields and relativistic particles are mixed with the gas as revealed by giant 'radio haloes', which arise from diffuse, megaparsec-scale synchrotron radiation at cluster centre[1,2]. Radio haloes require that the emitting electrons are accelerated *in situ* (by turbulence)[3–6], or are injected (as secondary particles) by proton collisions into the intergalactic medium[7–10]. They are found only in a fraction of massive clusters that have complex dynamics[11–14], which suggests a connection between these mechanisms and cluster mergers. Here we report a radio halo at low frequencies associated with the merging cluster Abell 521. This halo has an extremely steep radio spectrum, which implies a high frequency cut-off; this makes the halo difficult to detect with observations at 1.4 GHz (the frequency at which all other known radio haloes have been best studied). The spectrum of the halo is inconsistent with a secondary origin of the relativistic electrons, but instead supports turbulent acceleration, which suggests that many radio haloes in the Universe should emit mainly at low frequencies.

The turbulent re-acceleration model[5,6,15–17] for the origin of giant radio haloes assumes that fossil relativistic particles are re-accelerated by merger-induced turbulence to the energies necessary to produce the observed radio synchrotron emission in relatively weak magnetic fields. The acceleration of fast particles by turbulence, known to be an important process in astrophysics, is due to the resonant scattering of these particles by the turbulent waves (the energy spectrum of the turbulence can be thought of as the superposition of the contribution from turbulent waves with different length scales), leading to a stochastic energization of particles and to the damping of the waves[18]. The connection between mergers and particle acceleration by turbulence in galaxy clusters is complex. It is argued[15,19,20] that it should take place on a timescale of the order of a cluster–subcluster crossing time ($\sim$1 Gyr), during which turbulence is continuously injected on scales of the order of the subcluster size, transported at smaller scales and then dissipated into heating of the intergalactic medium and acceleration of relativistic particles over a fairly large volume. This argument is supported by recent radio observations of a complete sample of X-ray luminous clusters that allow a clear separation between clusters with radio haloes and radio-quiet clusters, suggesting, from the fraction of clusters with radio haloes, that the particle acceleration mechanisms operate sporadically, on timescales $\leq$1 Gyr and in connection with cluster mergers[21].

Abell 521 is an X-ray luminous (8.2×10^{37} W in the 0.1–2.4-keV band) and massive ($\sim 2 \times 10^{15}$ solar masses) galaxy cluster at redshift $z = 0.247$ with ongoing multiple merging episodes[22,23]. Here we report the discovery of a giant radio halo in this cluster by means of deep observations with the Giant Metrewave Radio Telescope (GMRT, India) at 240, 325 and 610 MHz. In Fig. 1a we show the radio image of Abell 521 at 240 MHz, where the radio halo is best imaged. To highlight the diffuse emission, point sources visible in the full-resolution images were subtracted in producing the low-resolution images in Fig. 1. The radio halo is coincident with the cluster X-ray emitting region and correlates with the X-ray emission of the hosting cluster, which is typical of other radio haloes[1,2] (see also Supplementary Information).

Previous higher frequency Very Large Array (VLA) observations at 1,400 MHz did not detect this diffuse emission, instead revealing only the radio relic located on the southeastern boundary of the cluster[23]. The relic coincides with a possible shock front, generated by recent in-fall of a subcluster along the northwest/southeast direction, where relativistic electrons are currently accelerated[24]. Figure 1 clearly shows that the radio halo becomes progressively more dominant over the radio relic at lower frequencies, indicating that its spectrum is much steeper than that of the relic, which has $\alpha \approx 1.5$ (ref. 24; flux is proportional to $\nu^{-\alpha}$, where ν denotes frequency). The patchy structure of the radio halo at 610 MHz (Fig. 1b) indicates the observational difficulty in imaging the emission, the surface brightness of which is already fading at this frequency. The halo disappears between 610 and 1,400 MHz; only an upper limit on the flux of the radio halo at 1,400 MHz can be derived, although faint residual emission in the cluster is still present at this frequency (Fig. 1c and Supplementary Information).

The flux densities of the radio halo at 240, 325 and 610 MHz are plotted in Fig. 2 together with the upper limits at 74 and 1,400 MHz. The upper limits were evaluated by injecting fake radio haloes with different flux densities into the observed data sets, following ref. 21, to estimate the sensitivity of the observations to diffuse emission on the halo length scale. In particular, the upper limit at 74 MHz was derived from VLA Low-frequency Sky Survey data[25], whereas the upper limit at 1,400 MHz was derived from the analysis of the archival VLA data (Supplementary Information). The important result is that the average value of the spectral index, $\alpha \approx 2.1$, is much larger than that of any other known radio halo (typical spectral index is $\alpha \approx 1.2$–1.3 (refs 1, 2)). These extreme spectral properties make Abell 521 a unique system for addressing the origin of the emitting particles in radio haloes.

Such an extremely steep spectrum and the downward spectral curvature (Fig. 2) imply a spectral cut-off at high frequency, which is a well-known signature of turbulent acceleration[4–6,16,17,19]. Synchrotron theory implies a corresponding cut-off in the spectrum of the emitting electrons at $E_e \approx 1.4 B_{nT}^{-1/2} (\nu_c/300)^{1/2}$ GeV, where ν_c is

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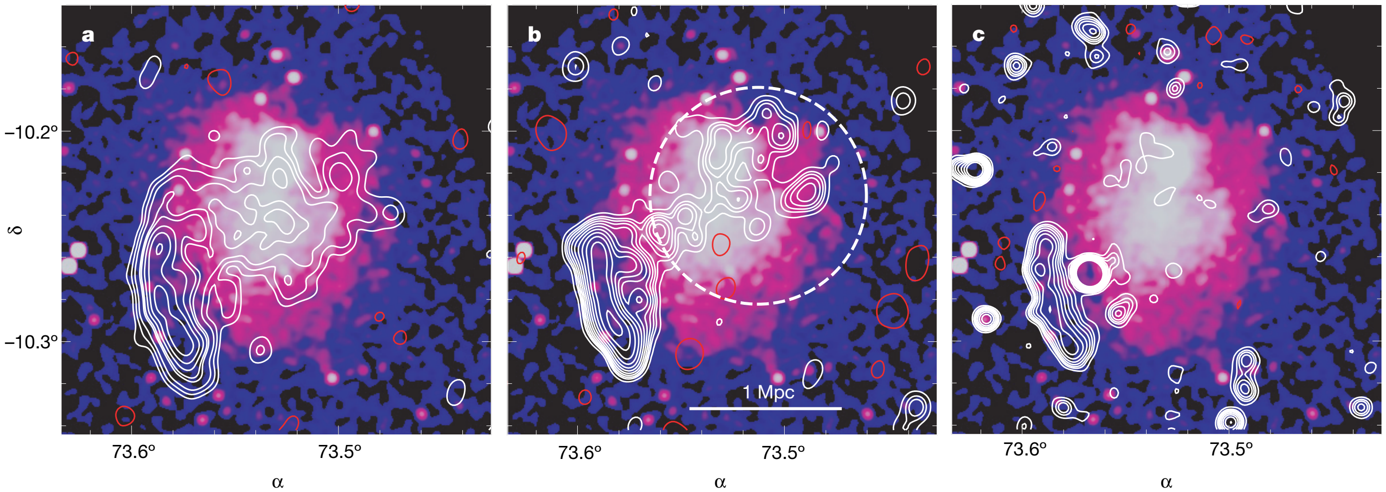

Figure 1 | Radio and X-ray images of Abell 521. Low-resolution radio contours (after subtraction of discrete sources in the field identified at full resolution) overlaid on the Chandra X-ray Observatory 0.5–4-keV X–ray image (corrected for background and exposure and smoothed with a $\sigma = 6$-arcsec Gaussian, as in ref. 24). **a**, GMRT 240-MHz contours at a resolution of 35 arcsec × 35 arcsec. The root-mean-square (r.m.s.) noise level in the cluster region was 220 μJy per beam (full beam resolution used for subtraction of discrete sources was 15.6 arcsec × 12.3 arcsec with an r.m.s. noise level of 190 μJy per beam). Contours are at −0.66 (red), 0.66, 1.3, 2.6, 5.2, 7, 10, 14 and 19 mJy per beam. **b**, GMRT 610-MHz contours at a resolution of 35 arcsec × 35 arcsec. The r.m.s. noise level in the cluster region was 58 μJy per beam (full beam resolution, 9 arcsec × 4 arcsec; r.m.s. noise, 35 μJy per beam). Contours are at −0.17 (red), 0.17, 0.34, 0.48, 0.67, 0.94, 1.3, 1.9, 2.6, 3.7 and 5.2 mJy per beam. The dashed circle indicates the region in which fluxes of the radio halo at the different frequencies (reported in Fig. 2) are measured. **c**, VLA 1.4-GHz contours at a resolution of 25 arcsec × 25 arcsec. Here only the discrete sources within 3 arcmin from the cluster centre were subtracted (other images are presented in Supplementary Information together with a discussion on the subtraction of discrete sources at this frequency). The r.m.s. noise level in the cluster region was 26 μJy per beam (full beam resolution, 12.7 arcsec × 6.9 arcsec; r.m.s. noise, 15 μJy per beam). Contours are at −0.08 (red), 0.08, 0.16, 0.22, 0.32, 0.45, 0.63, 0.89, 1.25, 1.76, 2.48, 3.5 and 4.9 mJy per beam. Coordinate system, J2000.

the cut-off frequency (measured in megahertz) and B_{nT} is the magnetic field (measured in nanotesla). In the framework of the turbulent acceleration scenario, E_e pinpoints the energy at which the timescale of the electron radiative losses becomes equal to that of the turbulent acceleration. The timescale of electrons emitting at ν_c is estimated taking into account the redshift-dependent inverse-Compton losses against the cosmic microwave background and the synchrotron losses[26], as follows, where ν_c is again measured in megahertz:

$$\tau \approx 0.95 \frac{B_{nT}^{1/2}(\nu_c/300)^{-1/2}}{(1+z)^4 + (B_{nT}/0.32)^2}\ \text{Gyr}$$

This means that the electrons responsible for the observed emission should be accelerated on a timescale of ~(1.1–1.4) × 10^8 years, for 0.1–0.5-nT magnetic fields in the radio halo region. Assuming that fast magnetosonic waves are responsible for the acceleration of the emitting particles, following ref. 20 we find that this acceleration efficiency can be achieved under the reasonable assumption that the energy density of these turbulent waves is ~12–18% of the thermal energy (Fig. 2).

Appreciable synchrotron emission can also be produced by secondary electrons injected by collisions between long-lived relativistic protons accumulated in the cluster and the thermal protons in the intergalactic medium, and secondary models have been proposed as alternatives to the re-acceleration model to explain radio haloes[7–10]. The very steep spectral slope of this radio halo rules out secondary models by means of a straightforward energy argument. To explain the spectrum of the radio halo through synchrotron radiation from secondary electrons, the primary protons must have a very steep spectral energy distribution ($N(p) \propto p^{-\delta}$, where $\delta \approx 4.2$ and p denotes the particle momentum). The energy density of relativistic protons, ε_p, required to match the observed synchrotron flux through a secondary model can be estimated following the formalism in ref. 27. For an average number density of thermal protons of $n_{th} \approx 1{,}500\ m^{-3}$ in the region of the radio halo (consistent with the average thermal density in the same region derived from X-ray observations[22]) and the synchrotron flux measured at 325 MHz, we find that ε_p ranges from approximately 3 to 100 times the energy density of the thermal plasma for magnetic field values (averaged in the region of the radio halo) ranging from $B = 0.5$ nT to $B = 0.1$ nT,

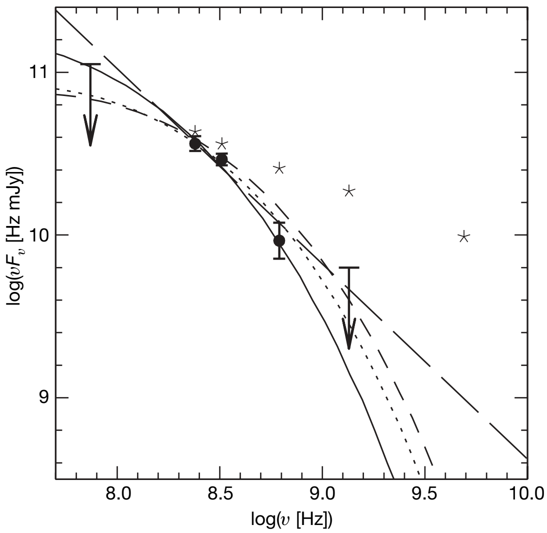

Figure 2 | Spectrum of the radio halo. Data are overlaid on secondary (long-dashed line) and re-acceleration models. Measured fluxes (F_ν) are 152 ± 15 mJy at 240 MHz, 90 ± 7 mJy at 325 MHz, 15 ± 3.5 mJy at 610 MHz, and limits (arrows) are 1.5 Jy at 74 MHz and 5 mJy at 1,400 MHz; uncertainties (and error bars in the figure) are 1 s.d. For comparison, asterisks give the spectral energy distribution of the radio relic (taken from ref. 24). The secondary model assumes that $\delta = 4.2$ and requires that the energy density of relativistic protons is larger than that of the thermal energy (see text). The re-acceleration models assume that 14% of the thermal energy is in magnetosonic waves, with a central value of the magnetic field of $B_o = 0.15$ nT (solid curve); that 14% of the thermal energy is in magnetosonic waves, with $B_o = 0.35$ nT (dotted curve); and that 18% of the thermal energy is in magnetosonic waves, with $B_o = 0.15$ nT (short-dashed curve). All the re-acceleration models adopt a scaling with $B \propto n_{th}$ (ref. 2 and refs therein).

respectively. This yields only a lower limit on the energy density of high-energy protons, because for $\delta > 3$ an additional (even dominant) contribution to the energy comes from suprathermal particles with kinetic energies <1 GeV. A secondary origin for the emitting electrons thus implies the unrealistic situation in which clusters are dominated by non-thermal protons. It also violates present upper limits on the energy density of these particles derived from γ-ray observations of several clusters, at the 20% level[28,29].

If the spectrum of these protons has $\delta < 4$, then the synchrotron signal from the secondary electrons produced by proton–proton collisions cannot exceed the 1.4-GHz upper limit in Fig. 2, placing corresponding limits on the energy density of the primary protons. Figure 3 shows upper limits on the energy density of the primary protons in the region of the radio halo as a function of the magnetic field. These limits were obtained following ref. 21 and show that the energy density of relativistic protons in the cluster is less than 1% of the thermal component for $B > 0.2$ nT and $\delta < 2.5$.

A similar conclusion has recently been reached in the analysis of a statistical sample of galaxy clusters without radio haloes[21]. However, in that case a larger energy content of protons was still possible by assuming that clusters without radio haloes have magnetic fields much smaller than those with radio haloes. This alternative (*ad hoc*) possibility can be reasonably ruled out in our case because Abell 521 hosts a radio halo with bolometric radio luminosity comparable to that of classical radio haloes ($\nu P(\nu) \approx 10^{34}$ W). Future observations with the Fermi Gamma-ray Space Telescope (formerly the Gamma-ray Large Area Space Telescope) will reveal galaxy clusters in γ-rays in cases where the energy content of relativistic protons is significantly larger than about 1% of the thermal plasma. The combination of this future data and limits in the radio band (Fig. 3 and ref. 21) may thus provide a powerful tool for constraining the magnetic field strength in galaxy clusters.

As we look at applying the turbulent re-acceleration model to other galaxy clusters, it should be stressed that the maximum energy to which electrons can be re-accelerated and, ultimately, the cut-off frequency in the spectra of radio haloes depend on the level of turbulence and on the properties of the turbulent waves. The spectral cut-off affects our ability to detect radio haloes in the Universe, introducing a strong bias against observing them at frequencies substantially larger than ν_c. Currently known radio haloes are mainly observed at gigahertz frequencies, requiring an efficient turbulent acceleration mechanism. These haloes must result from the rare, most energetic merging events and are therefore hosted only in the most massive, hottest clusters[19,30], in line with observations[11–14]. On the other hand, the majority of radio haloes should form during much more common, but less energetic, merging events, for example between a massive cluster and a substantially smaller subcluster (with mass ratio >5) or between two similar clusters with mass $\leq 10^{15}$ solar masses[19,30]. However, these sources, with a cut-off in the synchrotron spectrum at $\nu_c < 1$ GHz, should be visible only at lower frequencies, because their spectrum should be similar to that of the low-frequency radio halo in Abell 521. Future high-sensitivity radio telescopes operating at low frequencies, such as the Low Frequency Array and the Long Wavelength Array, are expected to discover the majority of these sources and also to test their connection with cluster mergers. At the moment this connection cannot be tested, owing to the lack of observations of samples of galaxy clusters at low radio frequencies.

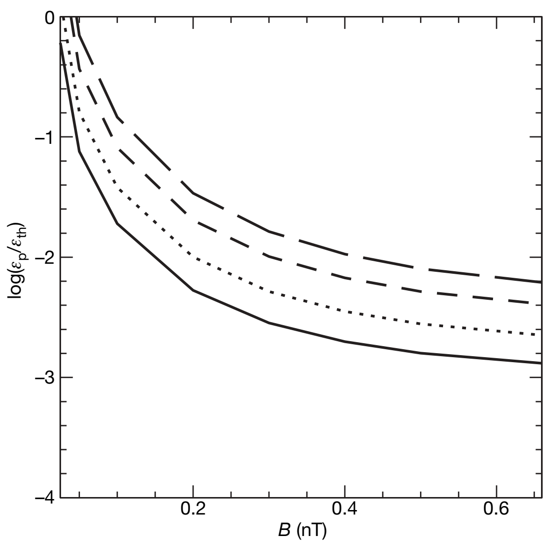

Figure 3 | Limits on the energy density of relativistic protons. Curves give the upper limit on the ratio between the energy density of relativistic protons and that of thermal gas, ε_{th}, as a function of the magnetic field in Abell 521. Calculations are shown assuming that $n_{th} = 1{,}500\ m^{-3}$ and $k_B T = 7$ keV, where T is temperature and k_B is Boltzmann's constant. From bottom to top, the spectral energy distributions of the primary protons have $\delta = 2.3, 2.5, 2.7$ and 2.9 ($N(p) \propto p^{-\delta}$).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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