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Supplementary Materials for

Gentle reenergization of electrons in merging galaxy clusters

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Supplementary material

Calculations

First of all we explain how we obtained the spectrum and brightness in Fig. 3 and the constraints on the reacceleration time-scale. We model the time evolution of the spectral energy distribution of electrons in the tail assuming the simple scenario where electrons are injected at time $t = 0$ and then evolve subject to energy losses and acceleration. We assume an initial spectrum of relativistic electrons $N_e(p,0) = K_e p^{-\delta}$ extending up to very high energies, and calculate its evolution with time using an isotropic Fokker-Planck equation

$$\frac{\partial N_e(p,t)}{\partial t} = \frac{\partial}{\partial p}\left[N_e(p,t)\left(\left|\frac{dp}{dt}\right|_{\rm r} + \frac{1}{3}\frac{dV/dt}{V}p - \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 D_{\rm pp})\right)\right] + \frac{\partial^2}{\partial p^2}\left[D_{\rm pp} N_e(p,t)\right] \quad (1)$$

where $|dp/dt|_r$ accounts for the radiative losses due to synchrotron and inverse Compton scattering with the photons of the cosmic microwave background radiation

$$\left|\frac{dp}{dt}\right|_{\rm r} \simeq 4.8 \times 10^{-4} p^2 \left[\left(\frac{B_{\mu G}}{3.2}\right)^2 + (1+z)^4\right] \quad (2)$$

where $B_{\mu G}$ is the magnetic field strength in units of μG; in Eq. 1 we neglect Coulomb (not relevant at the energies of the radio-emitting electrons) and adiabatic losses.

In Eq. 1, the term $\frac{1}{3}\frac{dV/dt}{V}p$ accounts for the compression/rarefaction rate, while D_{pp} is the electron diffusion coefficient in momentum space that is induced by a putative mechanism of reacceleration. The first term involving D_{pp} in the right hand of Eq. 1 represents a systematic acceleration rate, the second term involving D_{pp} induces a stochastic broadening of the electron spectrum.

The efficiency of the mechanism of reacceleration can be expressed in terms of reacceleration time, τ_{acc} (efficiency $= 1/\tau_{acc}$) The acceleration time depends on D_{pp} in Eq. 1

via

$$\tau_{acc} = p \left(\langle \frac{dp}{dt} \rangle \right)^{-1} = p^3 \left(\frac{\partial p^2 D_{pp}}{\partial p} \right)^{-1} \tag{3}$$

Results shown in Fig 3 (labelled "Model") are obtained by solving Eq. 1 under the assumption that acceleration is not operating for an initial period of time, Δt_{na} and that adiabatic expansion/compression is negligible. The comparison with the data requires a conversion between time and space/position. In doing that we assume that the relativistic plasma is left behind by the head of the tail and that the velocity of the tail/flow of the relativistic plasma is constant. Consequently space (distance from the head of the radio galaxy) is proportional to time.

The corresponding time/space-dependent synchrotron emissivity at the (emitted) frequency ν is obtained from

$$j(\nu, t) = \frac{e\sqrt{3}}{m_e c^2} \int_0^{\frac{\pi}{2}} d\theta B \sin^2\theta \int dp N_e(p,t) x \int_x^{\infty} K_{\frac{5}{3}}(z) dz \tag{4}$$

where $x(\theta, p) = 4\pi m_e^3 c^3 \nu p^{-2}/(3eB\sin\theta)$.

In practice, we assume different reacceleration times, τ_{acc}, and values of Δt_{na} to attempt to reproduce the data in Fig. 3. During the first phase of the evolution of the radio tail the spectrum can be fitted very well assuming a scenario where electrons simply age due to radiative losses. If we assume a velocity of the WAT similar to the dispersion velocity of the cluster $V, \sim 800$ km s $^{-1}$, the magnetic field that is required to match the spectral behaviour is near the conditions leading to a maximum age of the electrons emitting at a given frequency, i.e. $B \sim B_{\rm CMB}/\sqrt{3} \approx 2-2.5$ μG. Consequently in our modelling we adopt these parameters and attempt to reproduce the flattening of the spectrum that is observed at larger distances by assuming that a reacceleration mechanism becomes operative after Δt_{na}.

operative after Δt_{na}. This allows us to obtain a rough estimate of the reacceleration time that is necessary to explain the data during this second phase, $\tau_{acc} \sim 600 - 800$ Myr. Our simple interpretation is that gentle reacceleration mechanisms are turned on by a driver of internal perturbations in the tail that operates only after about 400 Myr , or that this driver is located within the ICM region that was crossed by the tail about 400 Myr ago. This provides a simple phenomenological explanation of our observations.

As a second step we explore the possibility that magnetic pumping can explain the acceleration rate/time-scale that is constrained by the radio data. Spatial perturbations/gradients of magnetic field are likely generated within ratio tails as a consequence of the complex interaction with the surrounding ICM. As a basic consequence relativistic electrons in the tails would interact with magnetic mirroring preserving the adiabatic invariant; this interaction per se does not necessarily induce particle acceleration. At the same time, however, relativistic electrons can be continuously scattered through the interaction with magnetic field perturbations on smaller scales. It is the combination of fast pitch-angle scattering and interaction with magnetic mirrors/bottles that may induce particle acceleration via a class of mechanisms that are known as betatron-acceleration or magnetic pumping (e.g. (36)). The acceleration time is

$$\tau_{acc} \sim \frac{\nu_{sc}}{\omega_{\Delta B}^2} \left(\frac{\Delta B}{B} \right)^{-2} \tag{5}$$

where $\omega_{\Delta B}$ is the frequency of long timescale magnetic field changes, ΔB, that induce magnetic mirrors/bottles in the radio tail and ν_{sc} is the pitch-angle scattering rate of radio emitting electrons.

In principle, mirroring and pitch-angle scattering of electrons can be due to two independent mechanisms. Large-scale magnetic mirrors may be induced by perturbations on larger scales, such as compression of the tail and instabilities due to the interplay between the relativistic plasma and the ICM shocks and turbulent motions. Consequently it is possible that this ingredient operates only under particular conditions, e.g. when the ICM is perturbed by a recent merger. Pitch-angle scattering can be induced by micro instabilities in the plasma and may be persistent, at some level, in radio sources in

general (50). According to Jaffe-Perola models, that nowadays are routinely used to fit the evolution of relativistic electrons in radio sources, this must happen on a time-scale that is much shorter than the electron life-time.

Of course it is difficult to derive the physical parameters in Eq. 5 from first principles. However it may be useful here to obtain a degenerate constraint on the conditions under which the mechanism can explain our data. We shall assume that magnetic field gradients/perturbations on large scales in the tail are established by the interaction with the ICM, leading to internal perturbations that oscillate with a frequency similar to the sound crossing time of the tail, $\omega_{\Delta B} \sim c_s r_{RT}^{-1}$ (c_s and r_{RT} being the sound speed in the ICM and the transverse size of the radio tail). Combining Eq. 5 with the value of the acceleration time that is required to explain the data, $\tau_{acc} \sim 700$ Myr, one obtains the following requirement on the pitch-angle scattering frequency of the electrons emitting at ≤ 100 MHz

$$\frac{\nu_{sc}^{-1}}{\text{yr}} \sim 2 \times 10^4 \left(\frac{r_{RT}}{30\text{kpc}}\right)^2 \left(\frac{c_s}{1000\text{km/s}}\right)^{-2} \left(\frac{\Delta B/B}{0.1}\right)^{-2} \tag{6}$$

that essentially means that a pitch-angle scattering rate in the head tail of tens of Myr may explain our observations.