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Particle Acceleration and Diffusion in Fossil Radio Plasma

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Abstract. The strong activity of radio galaxies should have led to a nearly ubiquitous presence of fossil radio plasma in the denser regions of the inter-galactic medium as clusters, groups and filaments of galaxies. This fossil radio plasma can contain large quantities of relativistic particles (electrons and possibly protons) by magnetic confinement. These particles might be released and/or re-energized under environmental influences as turbulence and shock waves. Possible connections of such processes to the formation of the observed sources of diffuse radio emission in clusters of galaxies (the cluster radio halos and the cluster radio relics) are discussed.

1. The Cosmological Energy Budget of Radio Plasma

The remnant of the radio lobes of a former active radio galaxy get rapidly invisible for radio telescopes, justifying the name *'radio ghosts'* for such patches of fossil radio plasma (Enßlin 1999a). Radio ghosts should be an important ingredient of the inter-galactic medium (IGM). The present space density of one or a few radio galaxies per galaxy cluster was exceeded by orders of magnitude during the epoch of violent quasar activity around $z = 2$. There are several routes to estimate the energy released by earlier radio galaxies. One is to integrate the evolution of the radio-luminosity-function, translated to jet-power via an empirical jet-power–radio-luminosity relation, based on equipartition energy densities of radio lobes. The result is (Enßlin & Kaiser 2000)

$$E_{\rm jet} = 3 \cdot 10^{66}\,{\rm erg\,Gpc}^{-3}\,(f_{\rm eq}/3)\,, \qquad (1)$$

where $f_{\rm eq}$ gives the ratio of true to equipartition energy density in the radio plasma, which is likely larger than one. This amount of energy corresponds to ~ 0.1 keV per cosmic baryon, and is therefore not negligible, since large-scale structure formation has produced ~ 1 keV/baryon by gravitational infall.

An independent route is to use the Magorrian relation ($\eta_{\rm bh} = M_{\rm bh}/M_{\rm bulge} = 0.002$) between the galaxy bulge ($M_{\rm bulge}$) and central black hole ($M_{\rm bh}$) mass. Assuming an efficiency of $\varepsilon_{\rm jet} = 0.1$ of rest mass to jet energy conversion of the accretion process feeding the black hole growth, one derives from the observed present day galaxy population (Enßlin et al. 1998b)

$$E_{\rm jet} = 3 \cdot 10^{67}\,{\rm erg\,Gpc}^{-3}\,(\eta_{\rm bh}/0.002)\,(\varepsilon_{\rm jet}/0.1)\,. \qquad (2)$$

If this estimate is correct, this amount of energy could easily provide the cosmic entropy-floor of 1 keV/baryon, which seems to be required in order to explain the X-ray luminosity–temperature relation of groups and clusters of galaxies.

Finally, a third way to estimate the energy in radio plasma is to assume that the efficiencies of accretion discs in active galactic nuclei (AGN) to produce X-rays and radio jets are the same. Assuming further that the observed X-ray background results only from unresolved AGN, one gets (Enßlin et al. 1998b)

$$E_{\rm jet} = 3 \cdot 10^{67}\,{\rm erg\,Gpc^{-3}}\,(\varepsilon_{\rm jet}/\varepsilon_{\rm X-ray})\,. \tag{3}$$

This should illustrate the importance of fossil radio plasma for IGM properties. A discussion of the possible influences of radio ghosts on various aspects of extra-galactic astrophysics can be found in (Enßlin 1999a) and (Enßlin 1999b). Here, recent progress on two of these aspects should be briefly reported: an attempt to estimate the escape rate of relativistic particles from radio ghosts (Enßlin 2000), and a new model for the revival of fossil radio plasma (Enßlin & Krishna 2000).

2. Adiabatic Revival of Fossil Radio Plasma

There is growing evidence that the so called *'cluster radio relics'* are tracers of shock waves in clusters of galaxies, as proposed in (Enßlin et al. 1998a). But these relics are rare compared to the frequency of cluster merger shock waves. This and the morphological connection between the relic 1253+275 in the Coma cluster and the tails of the radio galaxy NGC 4789 indicate that the locations which become radio luminous host fossil radio plasma. If this is indeed the case, the mechanism energizing the electron population is likely not Fermi-I shock acceleration. The reason for this is that an environmental shock wave is only capable of an adiabatic compression of the relativistic plasma. But due to the soft equation of state, even adiabatic compression can lead to a substantial energy gain of the electron population (Enßlin & Krishna 2000). If the fossil radio plasma was not too old, the upper cutoff of the electron energy spectrum might be adiabatically shifted to radio observable energies. Radio plasma younger than ~ 0.1 Gyr in the centers of galaxy clusters, and ~ 1 Gyr at peripheral regions can be revived to radio emission in typical shock waves. But this requires that the relativistic electrons are still confined to the radio ghost.

3. Particle Escape from Fossil Radio Plasma

All the plasma of a radio lobe was injected into the IGM from a very small region (the AGN) and expelled the IGM gas from a large volume. No magnetic flux can therefore leak from the radio plasma into the thermal environment, unless magnetic reconnection between these two phases took place. If such reconnection happened, the field topology could be partly opened, and relativistic particles would be able to leave the blob of radio plasma along an inter-phase magnetic flux tube. But also anomalous cross field diffusion might lead to particle losses. Typical escape frequencies of 10 GeV particles from fossil radio plasma are estimated in (Enßlin 2000). With the assumptions and parameters specified there (field strength $B = 10\,\mu$G, characteristic scales of the turbulence $l_B = \lambda_{||} = l_\perp = \lambda_\perp = 10\,$kpc, and a radio lobe diameter of 100 kpc) one gets a flux tube escape rate of $\nu_{||} \approx 2.0\,\mathrm{Gyr}^{-1}\,\eta_s/\varepsilon_0$, and a perpendicular escape rate of $\nu_\perp \approx 0.35\,\mathrm{Gyr}^{-1}\,\delta_0/\varepsilon_0$. $\delta_0 \leq 1$ gives the ratio of turbulent to total magnetic energy on the turbulence injection scale l_B, $\varepsilon_0 \leq 1$ describes the efficiency of particle pitch angle scattering, and $\eta_s \ll 1$ is the fraction of the lobe's surface threatened by inter-phase magnetic flux tubes. Particle losses are therefore slow even on cosmological time-scales.

These estimates assume a Kolmogorov turbulence cascade from the large scales, which are important for the anomalous particle transport across the field lines, down to the microscopic scales, responsible for pitch angle scattering and therefore fixing the parallel diffusion coefficient. If the shape of the spectrum is different, the results change. E.g., the presence of much stronger large scale turbulence can lead to the regime of enhanced anomalous diffusion.

If a cluster merger event suddenly injects large-scale turbulence, the radio plasma can get temporarily transparent even for low energy particles. Let's assume that the merger produces turbulent flows with velocities of $v_T \approx 1000\,\mathrm{km/s}$ on a scale of $l_T \approx 100\,$kpc which increase the turbulent magnetic energy density on large scales by a factor of $X_T = 30$ from initially $\delta_0 = 0.01$. For roughly an eddy turnover time $\tau_T = l_T/v_T \approx 100$ Myr the small scale turbulence is not increased. During this period an enhanced anomalous cross field escape should allow roughly $\tau_T\,\nu_\perp\,X_T^2 \approx 30\%/\varepsilon_0$ of the 10 GeV particles initially confined in the radio ghost to escape. The losses would even be much higher, if the pitch angle scattering efficiency is low ($\varepsilon_0 \ll 1$). The total loss of particles escaping along inter-phase flux tubes is $\tau_T\,\nu_{||}\,X_T \approx 6\%\,(\eta_\mathrm{s}/0.01)/\varepsilon_0 \ll 1$, and likely negligible if η_s is very small.

The release of relativistic protons from fossil radio plasma into the gaseous IGM might help to explain the observed *'cluster radio halos'* via hadronic secondary electron production (Enßlin 1999a,b).

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