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The Fate of Intracluster Radio Plasma

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Abstract. Radio plasma injected by active radio galaxies into clusters of galaxies quickly becomes invisible due to radiative losses of the relativistic electrons. In this talk, the fate of radio plasma and its role for the galaxy cluster is discussed: buoyancy removes it from the central regions and allows to transfer its energy into the ambient gas. The remaining low energy electron populations are still able to emit a low luminosity glow of observable radiation via synchrotron-self Comptonized emission. Shock waves in the ambient gas can re-ignite the radio emission.

1. Intracluster radio plasma

The jets of powerful radio galaxies inflate large cavities in the intracluster medium (ICM) that are filled with relativistic particles and magnetic fields. Synchrotron emission at radio frequencies reveals the presence of electrons with several GeV energies. These electrons have radiative lifetimes of the order of 100 Myr before their observable radio emission extinguishes due to radiative energy losses. The remnants of radio galaxies and quasars are called 'fossil radio plasma' or a 'radio ghosts' (Enßlin 1999). Their existence as a separate component of the ICM is supported by the detections of cavities in the X-ray emitting galaxy cluster gas (Böhringer et al. 1993; Carilli, Perley, & Harris 1994; Huang, & Sarazin 1998; McNamara et al. 2000; Fabian et al. 2000; Finoguenov & Jones 2001; Fabian 2001; McNamara 2000; Heinz et al. 2001; Schindler et al. 2001; and others). In many cases associated radio emission and in a few cases a lack of such emission was found, as expected for aging bubbles of radio plasma. Such bubbles should be very buoyant and therefore rise in the atmosphere of a galaxy cluster (Churazov et al. 2001). It is not clear yet if they break into pieces during their ascent and thereby are slowed down. Another possibility is that they are able to ascend up to the accretion shock of a galaxy cluster, where their further rise will be prohibited by the infalling gas of the accretion onto the cluster.

2. Rising bubbles

A rough estimate of the rise time of a bubble in a cluster potential can be obtained by balancing the buoyancy and the hydrodynamical drag forces (e.g. Enßlin & Heinz 2002 for further details). For a relativistic equation of state, which describes the expansion of the bubble due to the decreasing environmental pressure, such a bubble's rise is illustrated in Fig. 1. The parameters chosen

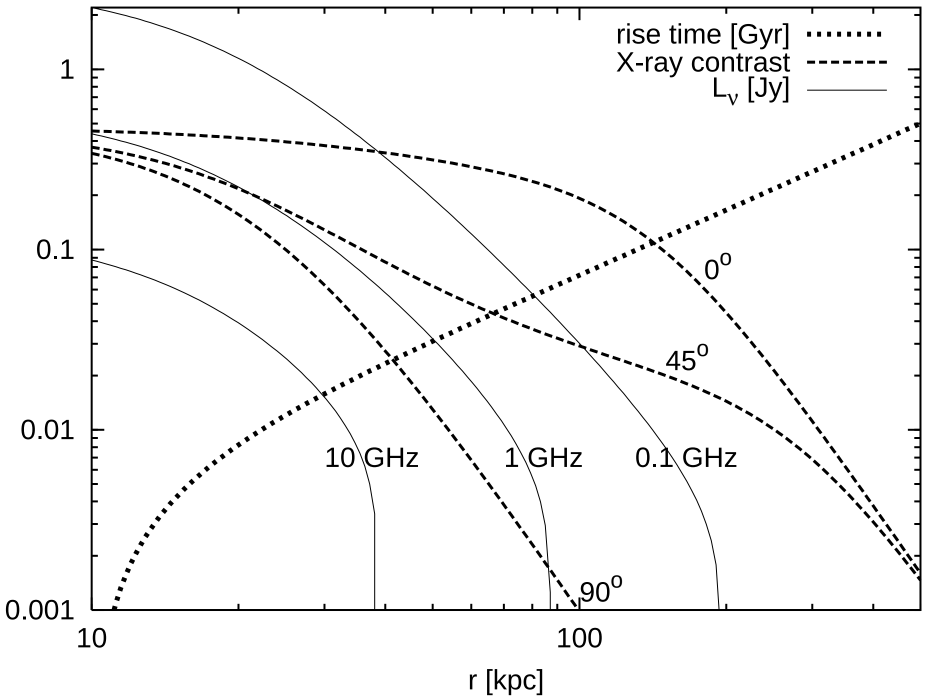

Figure 1. Bubble's central X-ray contrast (compared to the undisturbed cluster) for various angles between plane of sky and Bubble's trajectory, its radio flux, and its rising time as a function of the (unprojected) radial position. An X-ray background with 1/100 of the central cluster surface brightness is assumed, which is responsible for the strong decrease at large radii of the X-ray contrast in the 0° and 45° cases.

in this example are similar to the ones expected for one of the radio lobes of Perseus A.

Also the synchrotron luminosity at three different frequencies is shown in Fig. 1. Adiabatic losses dominate the decrease in radio luminosity, until the synchrotron and inverse Compton losses have removed all high energy electrons, and the sources fades completely. This happens first at higher frequencies due to the higher required electron energies necessary for high frequency synchrotron emission.

Further, the X-ray contrast of the bubble is shown in Fig. 1 for trajectories along the line of sight (0°), within the plane of sky (90°), and 45° in between of these two directions. From this it is clear, that the detectability of the bubble strongly depends on its 3-dimensional position within the cluster.

This is also illustrated in Fig 2, where the signal to noise ratio of an X-ray cavity at different positions in the cluster is displayed. The signal is the number of missing photons from the volume occupied by the cavity, and the noise is given by the typical photon number fluctuations for an undisturbed region (without cavity) at a comparable cluster radius and geometry (noise = the square root

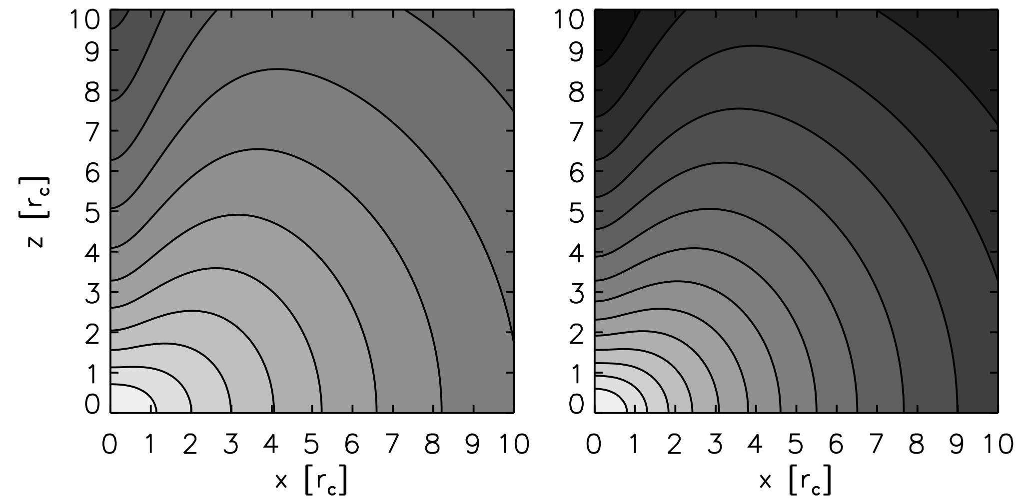

Figure 2. Contours of the X-ray deficit significance ($\mathcal{S}/\mathcal{N}$) of a bubble in a galaxy cluster. The contours mark locations at which a bubble has a significance which is lower by powers of 2 than its significance if located at the cluster center (in the lower left corner of each figure, vertical axis is parallel to the line of sight). Left: the bubble volume expands adiabatically (with a relativistic equation of state) with the pressure of the isothermal cluster. Right: the bubble volume is assumed to be independent of location (incompressible bubble, as a toy model). In both figures, an X-ray background with 1/100 of the central cluster surface brightness is assumed. For further details see Enßlin & Heinz (2002).

of the expected photon number). As can be seen there, the strongest signal to noise ratio is expected for a cavity within the central plane of the cluster. This implies, that the yet detected cavities are only a subsample of the cavities present, and therefore a larger subvolume of the ICM is likely be permeated by radio plasma than the present day maps indicate.

3. SSC & CMB-IC

Even very old radio plasma may be detectable by its long lasting very low frequency radio emission (kHz – MHz). Even if this emission is undetectable directly for terrestrial telescopes, it can be measured indirectly due to the unavoidable inverse Compton (IC) scattering of the synchrotron photons by their source electrons (Enßlin & Sunyaev 2002). These synchrotron self-Comptonized (SSC) photons have much higher energies and can therefore be in observable wavebands. The relativistic electron population also up-scatters every other present photon field. Photons of the cosmic microwave background (CMB) but also of the cosmic radio background (CRB) are removed from their original spectral location and shifted to much higher frequencies by IC encounters with the fossils radio plasma electron population. Since the frequency shift is large for

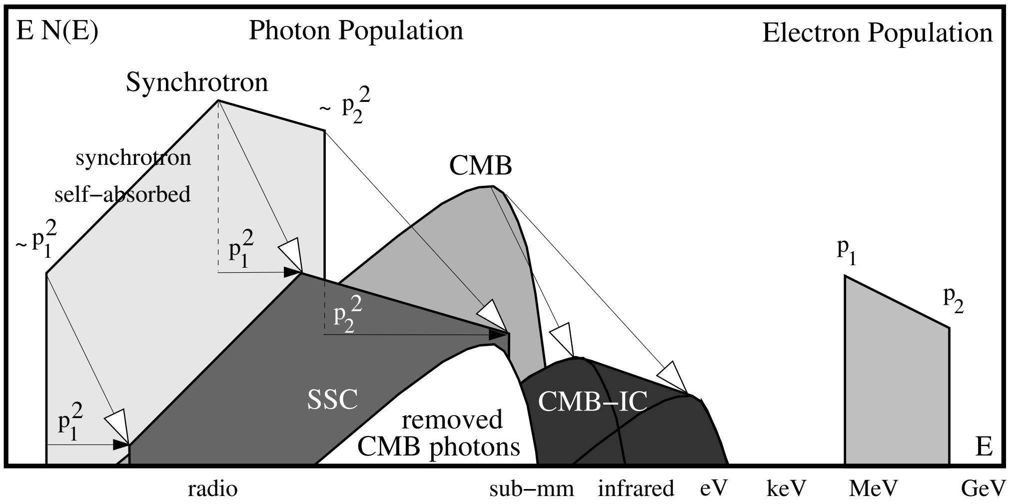

Figure 3. Sketch of the SSC and the CMB-IC process.

IC scattering by ultra-relativistic electrons, the CMB flux is decremented within the whole typical CMB frequency range (Enßlin & Kaiser 2001). The spectral signature of all these processes are sketched in Fig. 3.

The strongest detectable sources of such low frequency SSC emission should be radio lobes of just extinguished powerful radio galaxies (see Fig. 4 and Enßlin & Sunyaev (2002) for details). If for example the central engine of Cygnus A would decease today, its directly observable radio lobe synchrotron emission would vanish within some 10 Myr due to radiation and adiabatic losses of the (still) expanding radio plasma. But SSC and CMB-IC emission (or decrement) can remain for a few 100 Myr. Since the SSC emission is very sensitive to the compression state of the radio plasma it would decrease rapidly due to adiabatic expansion during the buoyant rise of the radio bubble in the cluster atmosphere. The CMB-IC process is much less sensitive to compression and would start to dominate the spectrum above 30 GHz after roughly 100 Myr.

The detection of SSC from radio ghosts is an observational challenge. It would be rewarded by revealing the locations of fossil radio plasma graveyards. It would provide important information on the lower end of the relativistic electron population. This would be very valuable since the electron energy range above a few 10 keV and below 100 MeV is still an unexploited spectral regions. Further, due to the strong dependence of the SSC emission on the compression stage of radio plasma, SSC emission is also a sensitive probe of the ICM pressure.

Due to its broad frequency spectra, it can be probed with several future high sensitivity instruments, ranging from lowest radio frequency radio telescopes as GMRT and LOFAR, over microwave spacecrafts like MAP and PLANCK, balloon and ground based CMB experiments, and sub-mm/IR projects as ALMA and the HERSCHEL satellites. A multi-frequency sky survey, as will be provided by the Planck experiment, should allow to search for the SSC and relativistic IC spectral signature of many nearby clusters of galaxies and radio galaxies, at least in a statistical sense by co-adding the signals from similar sources. In addition to this, there should be targeted observations of promising candidates,

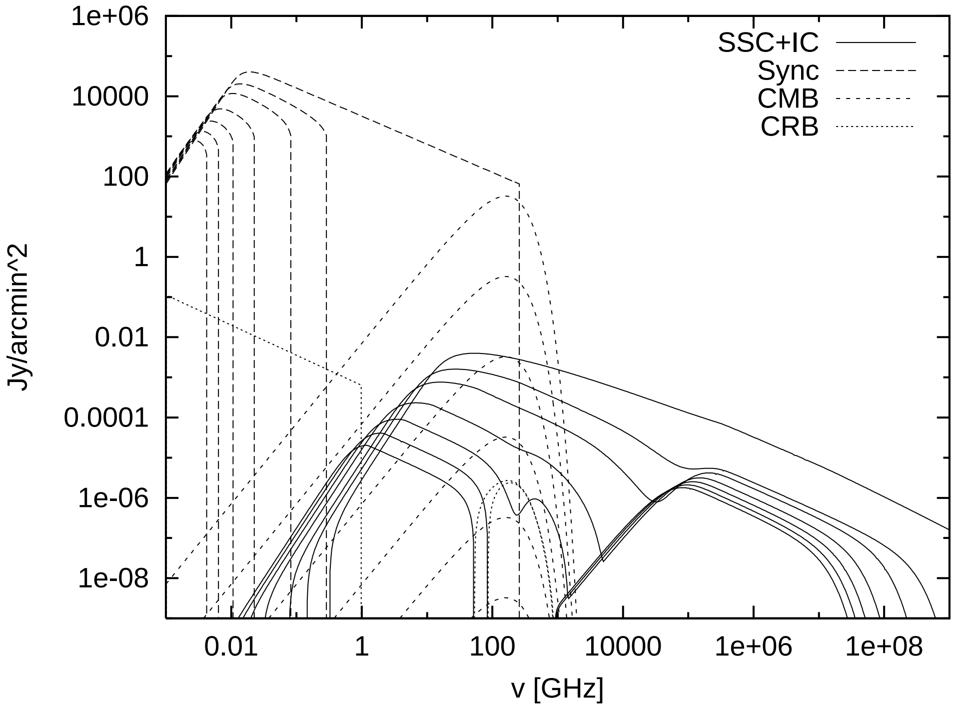

Figure 4. Central surface brightness of a Cygnus A-like radio cocoon in a cooling and expanding phase . The synchrotron (long-dashed) and SSC+IC spectra (solid) are shown for the stages at the jet-power shutdown and for later stages (from top to bottom spectra at ages of 0, 20, 40, 80, 120, 160, and 200 Myr are displayed). In spectral regions, where the SSC+IC processes lead to a reduction of the brightness below the CMB brightness, the absolute value of the (negative) SSC+IC surface brightness is plotted by a dotted line. The top one of the short-dashed lines is the CMB spectrum, the short-dashed lines below this are $10^{-2}, 10^{-4}, 10^{-6}, 10^{-8}$, and 10^{-10} times the CMB spectrum for comparison of the source to the CMB brightness. The dotted power-law line at frequencies below 1 GHz is the cosmic radio background (CRB)

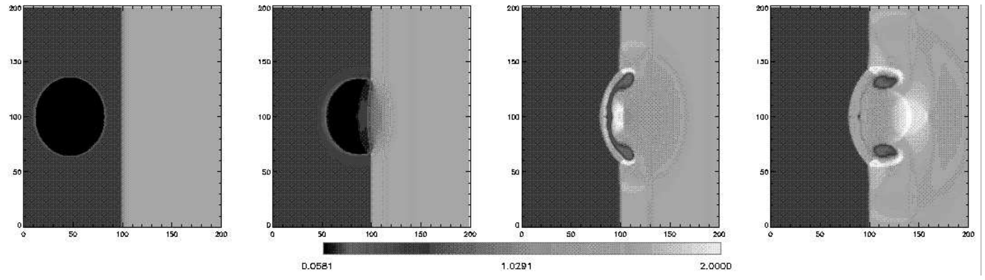

Figure 5. Shock passage of a hot, magnetized bubble (a radio ghost) through a shock wave. The flow goes from the left to the right. The evolution of the mid plane gas density is displayed (white is dense, black is dilute gas)

as e.g. the recently reported X-ray cluster cavities without apparent observable synchrotron emission. New and upcoming radio telescopes like LOFAR, GMRT, EVLA, ATA, and SKA should have a fairly good chance to detect such sources. E.g. a Cygnus-A like radio cocoon should be detectable for these telescopes out to a few 100 Mpc even $\sim$ 100 Myr after the jetpower shutdown (Enßlin & Sunyaev 2002).

4. Shock wave re-illumination

Whenever a radio ghosts is hit by a shock wave, which may originate either from a cluster merger or from the steady accretion of gas onto the still forming large scale structure, it is strongly compressed. The compression should be adiabatic since typical ICM shock speeds of a few 1000 km/s are expected to be well below the internal sound speed of the fossil but still relativistic plasma. Since the radio plasma has to adapt to the new ambient pressure, the compression factor can be high and the particles and magnetic fields can gain a substantial amount of energy. The synchrotron emission can go up by a large factor, especially at frequencies which were only a little bit higher than the cutoff frequency of the uncompressed fossil plasma (Enßlin & Gopal-Krishna 2001). Thus, the radio plasma can be revived to emit at observing frequencies if it was not too old, a few 100 Myr inside and a few Gyr at the boundary of galaxy clusters.

3-D magneto-hydrodynamical simulations (Enßlin & Brüggen 2002) show that during the traversal of a shock wave, the radio plasma is first flattened and then breaks up into small filaments, often in form of one or several tori. The formation of a torus can be seen in Fig. 5. At places where the hot, under-dense radio plasma bubble touches the shock wave the balance of pre-shock ram-pressure and post-shock thermal pressure disappears due to the lack of substantial mass load of the advected radio plasma. The post shock gas therefore starts to break through the radio plasma and finally disrupts it into a torus or a more complicated filamentary structure.

The magnetic fields becomes mostly aligned with the filaments leading to a characteristic polarization signature which can be seen in the synthetic radio map displayed in Fig. 6.

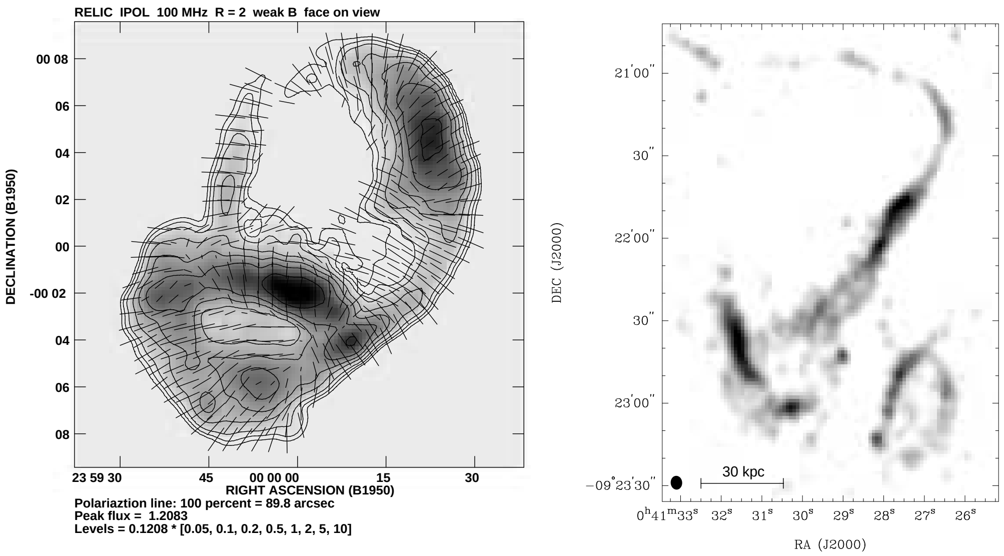

Figure 6. Left: synthetic radio map of a shocked radio ghost (Enßlin & Brüggen 2002). Right: observed cluster radio relic in Abell 85 at 1.4 GHz (Slee et al. 2001)

Polarized radio emitting regions of often filamentary morphologies could be found in a (recently strongly growing) number of merging clusters of galaxies. In most cases they are near those places where shock waves are expected from either observed temperature structures or comparison of X-ray maps to simulated cluster merger. These radio sources are called cluster radio relics (Feretti 1999, and references therein). An observed radio map of a filamentary cluster radio relic in Abell 85 is also displayed in Fig. 6 for comparison. Lower frequency observation show that the upper filament of this relic forms (at least in projection) a closed torus (Giovannini & L. Feretti 2000).

Thus, sensitive observation of cluster radio relics are able to probe several properties of ICM shock waves. Since the major diameter of the fossil radio plasma is approximately conserved, a rough estimate of the compression factor can be derived from relic radio maps by measuring the filament diameters. The compression factor depends only on the pressure jump in the shock and the equation of state of the radio plasma. Therefore, the shock strength is measurable for a given radio plasma equation of state. Or, if detailed X-ray maps allow to estimate the shock strength independently, the equation of state of radio plasma can be measured. Furthermore, the total radio polarization of cluster radio relics (after averaging over the source) contains in principle enough information to entangle the 3-D orientation of the shock wave: The sky-projected electric vector is aligned with the projected shock normal. The polarization fraction is highly correlated with the angle between the shock normal and the line of sight (Enßlin & Brüggen 2002).

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