arXiv:astro-ph/0112386 v1 17 Dec 2001

# Tracing the Remnants of Powerful Quasars to Probe the IGM

Torsten A. Enßlin[1], Rashid A. Sunyaev[1,2], and Marcus Brüggen[1,3]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str.1, Postfach 1317, 85741 Garching, Germany
[2] Space Research Institute (IKI), Profsoyuznaya 84/32, Moscow 117810, Russia
[3] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, United Kingdom

**Abstract.** Powerful quasars and radio galaxies are injecting large amounts of energy in the form of radio plasma into the inter-galactic medium (IGM). Once this nonthermal component of the IGM has radiatively cooled the remaining radio emission is difficult to detect. Two scenarios in which the fossil radio plasma can be detected and thus be used to probe the IGM are discussed: a) re-illumination of the radio emission due to the compression in large-scale shock waves, and b) inverse Compton scattered radiation of the cosmic microwave background (CMB), cosmic radio background (CRB), and the internal very low frequency synchrotron emission of the still relativistic low energy electron population. We present 3-D magneto-hydrodynamical simulations of scenario a) and compare them to existing observations. Finally, we discuss the feasibility of the detection of process b) with upcoming instruments.

## 1 Fossil Radio Plasma

The jets of powerful radio galaxies inflate large cavities in the IGM that are filled with relativistic particles and magnetic fields. Synchrotron emission at radio frequencies reveals the presence of electrons with 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' [1]. Their existence as a separate component of the IGM is supported by the detections of cavities in the X-ray emitting galaxy cluster gas [2,3,4,5,6,7,8,9,10,11, 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. 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 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

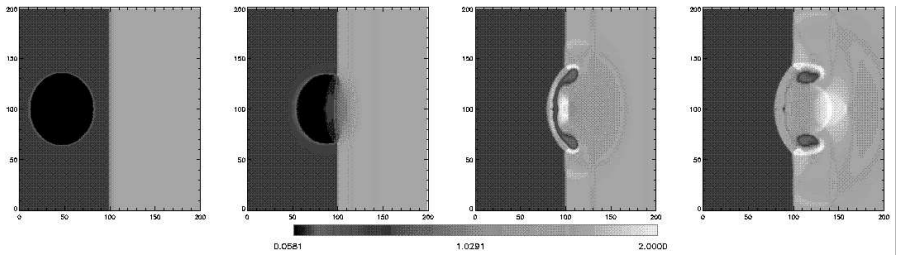


**Fig. 1.** Shock passage of a hot, magnetized bubble (a radio ghost) through a shock wave. The flow goes from the left to the right. The evolution of the mid plane gas density is displayed (white is dense, black is dilute gas)

scale structure, it is strongly compressed. The compression should be adiabatic since typical IGM 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 [12]. Thus, the radio plasma can be revived to emit at observing frequencies if it was not too old, a few 100 Myr inside and few Gyr at the boundary of galaxy clusters.

3-D magneto-hydrodynamical simulations [13] 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. 1. 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. 2.

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 [14, and references therein]. An observed radio map of a filamentary cluster radio relic in Abell 85 is also displayed in Fig. 2 for comparison. Lower frequency observation show that the upper filament of this relic forms a closed torus [15].

Thus, sensitive observation of cluster radio relics are able to probe several properties of IGM shock waves [13]. Since the major diameter of the fossil radio plasma is approximately conserved, a rough estimate of the compression factor

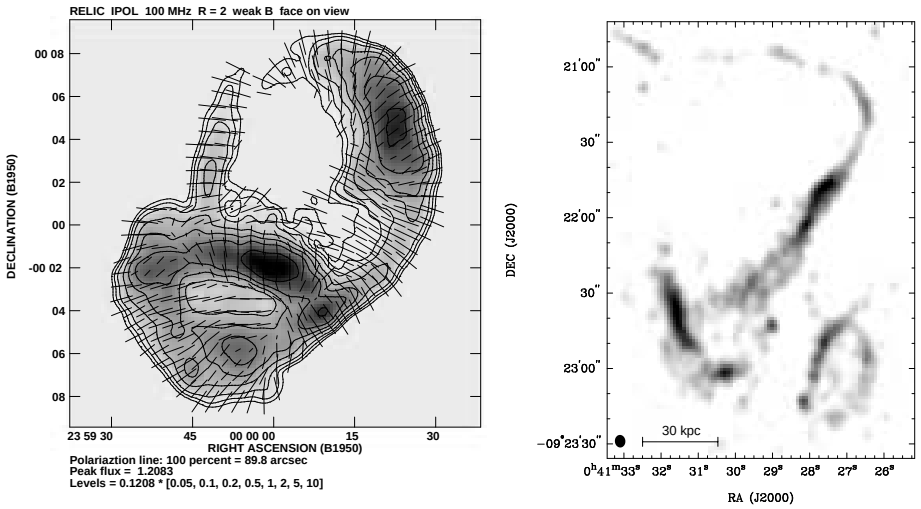


**Fig. 2.** Left: synthetic radio map of a shocked radio ghost [13]. Right: observed cluster radio relic in Abell 85 at 1.4 GHz [16]

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 [13].

## 3 SSC & CMB-IC

But 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 [17]. 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 IC scattering by ultra-

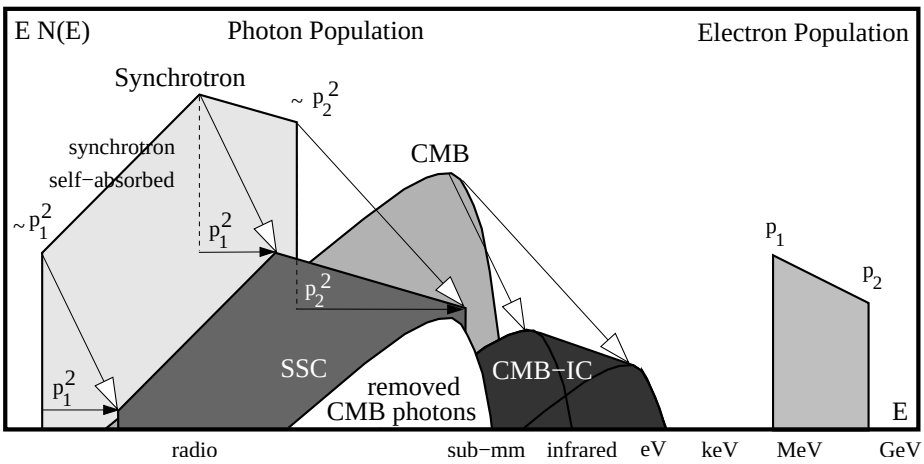


**Fig. 3.** Sketch of the SSC and the CMB-IC process

relativistic electrons, the CMB flux is decremented within the whole typical CMB frequency range [18]. The spectral signature of all these processes are sketched in Fig. 3.

The strongest sources of such low frequency SSC emission should be radio lobes of just extinguished powerful radio galaxies (see Fig. 4 and [17] 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.

Also our own galaxy might have produced radio ghosts during earlier active phases of the central black hole. Owing to the low density environment of the local group (compared to the Cygnus A galaxy cluster) such a ghost is expected to be very relaxed and to have a very low surface brightness (see Fig. 4). But it may be detectable because of its large angular scale. If further environmental compression would have increased its SSC and CMB-IC glow (in the displayed model a compression by a factor 11 in a 10 Gyr period was assumed) a future detection may be possible.

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,

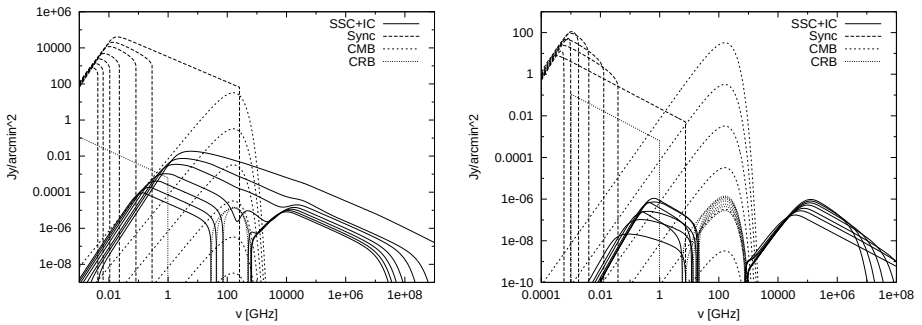


**Fig. 4.** Central surface brightness of a Cygnus A-like radio cocoon in a cooling and expanding phase (left) and of a possible radio ghost produced by our own galaxy during cooling and moderate compression (right). The synchrotron (long-dashed) and SSC+IC spectra (solid) are shown for the stages at the jet-power shutdown and for later stages (left: from top to bottom spectra at ages of 0, 20, 40, 80, 120, 160, and 200 Myr are displayed; right: from bottom to top spectra at ages of 0, 1, 2, 4, 6, 8, and 10 Gyr 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)

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 IGM 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 [18]. In addition to this, there should be targeted observations of promising candidates, as e.g. the recently reported X-ray cluster cavities without apparent observable synchrotron emission. New and upcoming lower frequency ($\leq$ 10 GHz) radio telescopes like LOFAR, GMRT, EVLA, and ATA 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 [17].

We hope that this work stimulates observational efforts to exploit the spectral landscape of the *terra incognita* of 1-100 MeV electrons residing in the intergalactic space via their combined SSC and CMB-IC emission.

## References


1. T. A. Enßlin: In *Diffuse Thermal and Relativistic Plasma in Galaxy Clusters*, (1999) pp. 275, astro-ph/9906212
2. H. Böhringer, W. Voges, A. C. Fabian, A. C. Edge, D. M. Neumann: *MNRAS*, 264, L25–L28 (1993)
3. C. L. Carilli, R. A. Perley, D. E. Harris: *MNRAS* 270, pp. 173 (1994)
4. Z. Huang C. L. Sarazin: *ApJ* 496, pp. 728 (1998)
5. B. R. McNamara, M. Wise, P. E. J. Nulsen, L. P. David, C. L. Sarazin, M. Bautz, M. Markevitch, A. Vikhlinin, W. R. Forman, C. Jones, D. E. Harris: *ApJ Lett.* 534, pp. L135–L138 (2000)
6. A. C. Fabian, J. S. Sanders, S. Ettori, G. B. Taylor, S. W. Allen, C. S. Crawford, K. Iwasawa, R. M. Johnstone, P. M. Ogle: *MNRAS* 318, pp. L65–L68 (2000)
7. A. Finoguenov, C. Jones: *ApJ Lett.* 547, pp. L107–L110 (2001)
8. A. C. Fabian: In D. M. Neumann, editor, *XXIth Moriond Astrophysics Meeting on 'Galaxy Clusters and the High Redshift Universe Observed in X-rays'*, 2001.
9. B. R. McNamara: In F. Durret & D. Gerbal, editor, *Constructing the Universe with Clusters of Galaxies*, IAP (Paris, 2000) astro-ph/0012331.
10. S. Heinz, Y.-Y. Choi, C. S. Reynolds, M. C. Begelman: *ApJ Lett.* submitted (2001).
11. S Schindler, Castillo-Morales A, E De Filippis, A Schwope, J. Wambsganss: *A&A* submitted (2001)
12. T. A. Enßlin, Gopal-Krishna: *A&A* 366, pp. 26–34 (2001)
13. T. A. Enßlin, M. Brüggen: *MNRAS* in press (2001) astro-ph/0104233
14. L. Feretti: In *Diffuse Thermal Relativistic Plasma in Galaxy Clusters* (1999) pp. 3
15. G. Giovannini, L. Feretti: *New Astronomy* 5, pp. 335–347 (2000)
16. O. B. Slee, A. L. Roy, M. Murgia, H. Andernach, M. Ehle: *AJ* 297, pp. 86 (2001)
17. T. A. Enßlin, R. A. Sunyaev: *A&A* in press (2001) astro-ph/0107432
18. T. A. Enßlin, C. R. Kaiser: *A&A* 360, pp. 417 (2000)