Proceedings of The Magnetized Plasma in Galaxy Evolution
Sep. 27th – Oct. 1st 2004, Jagiellonian University, Kraków, Poland
Eds. K.T. Chyży, K. Otmianowska-Mazur, M. Soida and R.-J. Dettmar

Energy and magnetic field beyond clusters: expectation and evidence

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Abstract

Both recent observational evidence, and physical arguments suggest that magnetic fields are very widespread in the IGM beyond clusters. There is less direct, but compelling evidence that the same was true at earlier cosmological epochs at z $\sim$ 4 - 10 and beyond. Recent observational evidence from Faraday rotation data, low-level extragalactic synchrotron radiation, and analyses of BH-powered extragalactic radio sources enable us to obtain new, quantitative estimates of the magnetic and cosmic ray energy in the wider intergalactic space. Some implications of these emerging facts will be briefly discussed.

1 Introduction

Accretion onto a presumed central supermassive black hole is the favoured energy source for the powerful radio sources (e.g. Begelman, Blandford, & Rees 1984). Colgate & Li (1999, 2000), Colgate, Li, & Pariev (2001) and others have argued that such sytems can provide a strong feedback effect on the dynamics of the intergalactic medium (IGM). A significant fraction of the energy released during the formation of galactic black holes appears to have been directly converted into magnetic field energy and magnetic flux. Observations confirm that these are efficiently injected into extragalactic space. Subsequent cosmic ray (CR) diffusion into the IGM continues this process further.

The fact that extragalactic radio sources are seen in synchrotron radiation enables an approximate calculation of the minimum energy contained in the sources' magnetic fields and relativistic particles. The largest, Mpc - scale "giant" radio galaxies(GRG's) are the best calorimeters of central black hole (BH) energy release in the sense that they retain more of the BH-released energy in a visible form than other system (Kronberg *et al.* 2001). Their typical "visible" energy content, $10^{60} - 10^{61}$ ergs, is possibly even conservative by a factor of a few. This requires a very high conversion efficiency of the central BH's infall energy into magnetic fields and cosmic ray (CR) particles (Kronberg *et al.* 2004).

The efficient transport of this enormous energy into the intergalactic medium means that it should be detectable as diffuse synchrotron radiation at cm and meter radio wavelengths, and/or as inverse Compton scattering of CMB photons off the CR electrons, visible in EUV and X-ray bands. The consequent heating of the IGM might also be visible as thermal emission, or more readily in absorption lines by hot intergalactic gas, the "WHIM".

In this contribution I review observational evidence from low level diffuse intergalactic radio emission, that supports the existence of widespread AGN-BH feedback into the IGM and its attendant magnetization. I show global calculations that provide a quantitative basis for expecting some widespread, diffuse nonthermal emission at a detectable level. I also briefly discuss evidence for the existence of μG - level magnetic fields in galaxy systems at high redshift. Measurements of this type are of great importance for understanding the evolution of large scale structure in the Universe, the early evolution of galaxies, and the early origins of intergalactic magnetic fields. Much of the discussion incorporates analysis and arguments laid out in two recent papers and references therein: Kronberg, Dufton, Li & Colgate (2001), and Kronberg, Colgate, Li & Dufton (2004).

2 Magnetic energy as "captured" energy release from galactic black holes

A substantial fraction of the energy stored in extended extragalactic radio sources appears to be in the form of magnetic energy. This is different from other forms of energy release, such as the radiation from AGNs. The photon energy quickly loses its dynamical impact when the surrounding medium becomes optically thin, at which point it is carried away at $v = c$. The magnetic energy, by contrast, gets retained/confined within a much smaller IGM volume (large compared to the "engine" size but much smaller than what the radiation will fill) for a significant fraction of cosmic time (Kronberg et al. 2001). Gopal-Krishna and Wiita (2001) and Furlanetto and Loeb (2001) have produced calculations to show that the global IGM filling factor of radio lobes is a significant fraction of unity. Similar IGM filling factors were estimated by Kronberg, Lesch and Hopp (1999), who calculated the minimum IGM magnetic field volume filling factor using only models of starburst halos for primeval galaxies beginning at z ~10. They arrived a similar conclusion, namely that star-driven outflows by themselves would fill a significant fraction of the IGM filament volume by z ~7 (see Figure 1).

An important consequence of outwardly transported magnetic fields is that they can remain *dynamically* important, perhaps for most of a Hubble time, because they may interact more strongly with the surrounding IGM than will the radiation. Gopal-Krishna Wiita & Osterman (2003) consider the triggering of star formation by AGN-powered radio jets and lobes and their consequences for the magnetization of the Universe.

3 BH energy release to the IGM in the low -z universe

A simple calculation of the global energization of the IGM can be made by combining the BHs' dynamically estimated masses (Tremaine *et al.* 2002), low z bright galaxy surveys, and the gravitational infall energy reservoir per galactic BH, $E_{\rm infall}$

$$E_{\rm infall} = M_{BH}c^2 = 1.8 \times 10^{62} \frac{M_{BH}}{10^8 M_\odot} \text{ergs} \tag{1}$$

Equation (1) assumes infall of the entire BH mass to the Schwarzschild radius, R_S. Comoving values of ρ_{BH} are

$$\rho_{\rm BH} \sim 2.2 \times 10^5 \ {\rm M_\odot \ Mpc^{-3}} \tag{2}$$

(Choksi & Turner 1992, Pinkney *et al.* 2003).

To this information we combine radio observation-based estimates of the energy that is fed into radio source lobes from their parent BH. As Kronberg *et al.* (2001) argue, the uniquely large energy content of GRG's make them the best available *calorimeters* of central BH energy conversion into CR's and magnetic fields.

Combining $\rho_{\rm BH}$ with (1) gives a global, space-averaged total IGM energy density, asuming 100% conversion efficiency from gravitational energy to R_S. The average, smoothed out IGM

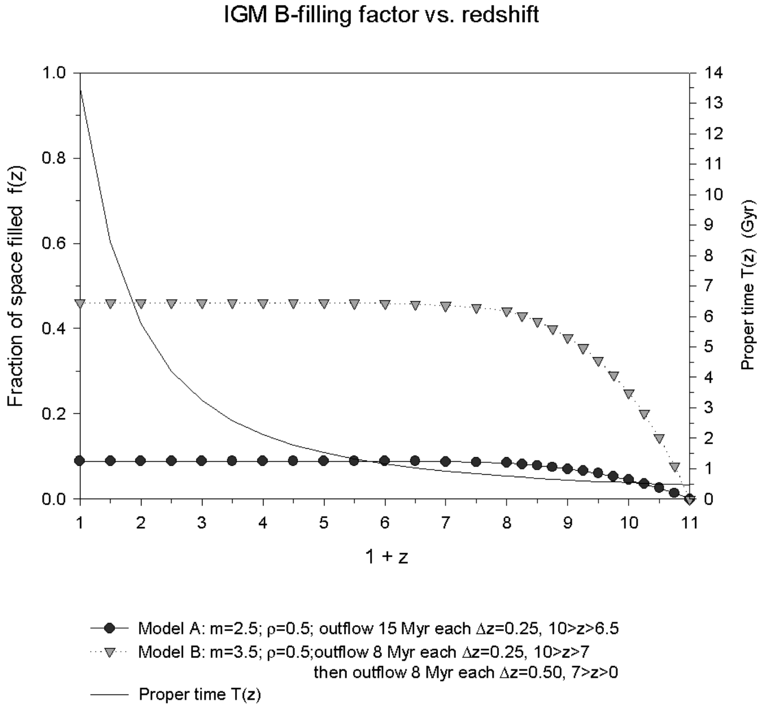

Figure 1: Fraction of the galaxy filament volume IGM filled with magnetized plasma due to collective starburst outflows in primeval galaxies that are assumed to start at z = 10. The Proper Time scale is on the right axis. For further details on the model parameters refer to Kronberg, Lesch & Hopp (1999)

energy density due to the BH - radio jet/lobe engines is $e \sim 10^{-14}$ erg/cm^3, scaled to an average BH mass of $10^8 M_\odot$. Note that this average applies to a homogeneous IGM, and ignores filaments and walls.

To arrive at a global estimate of the i.g *magnetic* energy density that is spread into the filaments of LSS, we need to scale this number by $(\epsilon_B)\times(f_{filament})^{-1}\times(f_{RG})$, where ϵ_B, is the fraction of BH energy released by the host galaxy as magnetic energy, and f_{RG} is the fraction of galaxies with central BH's that produced a radio galaxy or RLQSO over a Hubble time. Note that the latter number will be higher than the present fraction of radio loud galaxies because a typical radio-visible lifetime is $\lesssim 10^9$ years, i.e. $\lesssim 0.1$ of a Hubble time. I assume that much of the released magnetic energy accumulates over a Hubble time, and that some re-acceleration of the CR electrons occurs to make them visible at radio fequencies below $\sim$ 1GHz.

For the purpose of simple global estimates I use $\epsilon_B = f_{filament} = f_{RG} = 0.1$ as a convenient set of fiducial values. This gives an estimate $e_B \sim 10^{-15}$ erg/cm^3, and a corresponding $B_{IGM} \sim 1.6\times10^{-7}$G.

Large scale compression and infall shocks in LSS would add further energy to the intergalactic magnetoplasma over time (Ryu, Kang & Biermann 1998, Ryu *et al.* 2003). The magnetic field strengths deduced by these authors for the galaxy filaments is of comparable order, and is consistent with global gravitational infall energies in LSS- and galaxy-formation. Actual computation of magnetic field evolution in LSS is both challenging and rewarding. It must include full 3-D simulations of LSS evolution that include all the magnetic field amplification processes, gas cooling, etc.

4 Observational evidence for sub-microgauss intergalactic magnetic fields

Adapted from **: Kim, Kronberg, Giovannini and Venturi, NATURE, 1989**

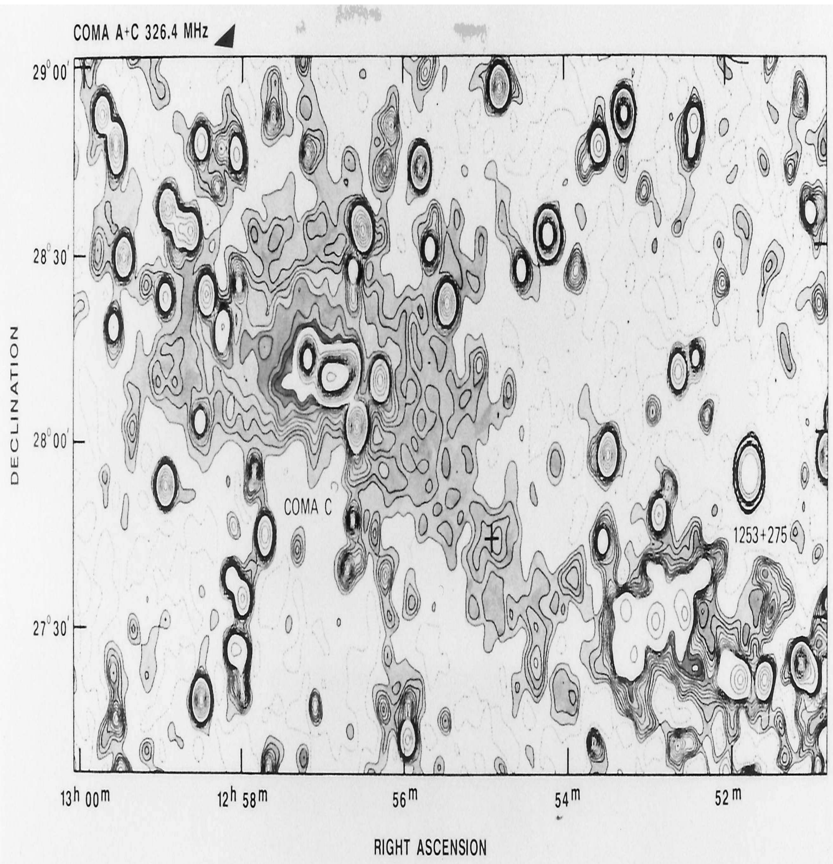

Figure 2: WSRT 324 MHz image of a 2.5° × 2.5° field centered slightly south and west of the Coma cluster. The image was made from a combination of 6 12-hr WSRT sessions, each with a different setting of the moveable telescopes for optimum uv-coverage. The rms noise level was 1.1 mJy/beam, and the beam size in this image is 2′ EW × 4′ NS. (Adapted from Kim, Kronberg, Giovannini & Venturi, 1989)

The first firm detection of diffuse synchrotron radiation beyond galaxy clusters was ob-

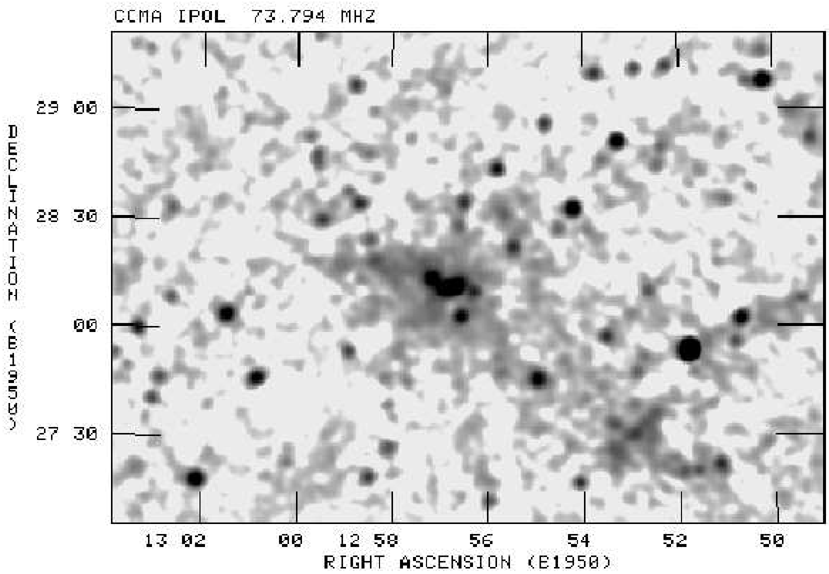

Figure 3: Central part of the 74 MHz VLA image of part of the Coma Supercluster that confirms the diffuse bridge emission between the Coma Cluster and the "relic source" to the SW that is seen in Figure 2 at 327 MHz. Other diffuse intergalactic emission can be seen in the figure. (Enßlin et al. 1999).

tained by Kim, Kronberg, Giovannini and Venturi (1989), using 326 MHz imaging of a 3 $^{\circ}$ area around the Coma cluster of galaxies. Their image is shown in Figure 2. It has an rms noise level of 1.1 mJy/beam and a resolution of $2'$ EW $\times$ $4'$ NS. Kim *et al.* (1989) concluded intergalactic *inter*cluster magnetic field strengths in the range of 0.3 - 0.6 μG over an intergalactic region 1 - 2 Mpc in extent, outside the Coma Cluster. These values are in line with the “expectation” field strengths derived purely from galactic BH - IGM feedback arguments that we summarized above.

Instrumental aspects and antenna aperture theory are important to consider when attempting to optimally image radio brightness distributions on a wide range of scales: Despite the high sensitivity of the image in Figure 2, its Fourier transform (uv-plane data) is missing the lowest order spatial harmonics because of the 25m. size of the WSRT antennas prevents the uv-plane sampling of Fourier components that are lower than $\sim$75λ. This is evident in a negative “bowl” which is difficult to see in Fig. 2, but it indicates that additional large scale structures are present that are not represented in this image. To correct this limitation, we have recently obtained a single dish raster-scanned 0.3 GHz image with the Green Bank 110m Telescope (GBT), and are in the process of making an improved image with all Fourier components present, also including more recent all-configuration VLA observations at 0.3 GHz (Kronberg, Perley, Kassim, Giovannini and Cotton *in prep* (2005). A combined single dish-interferometer image of the Coma region at 408 MHz by Kim *et al.* (1989) also revealed a component of extended, *supra*-cluster synchrotron emission. Analysis of new 408 observations with the upgraded DRAO Interferometer, combined with Arecibo and Effelsberg single dish observations at this higher frequency band is in progress (Kronberg, Kothes, Salter and Perillat in prep.).

An all-configuration VLA image at the low frequency of 74 MHz of a wider field containing the Coma cluster is shown in Figure 3 (Enßlin et al. 1999). Further faint and diffuse intergalactic emission can be seen in a horseshoe-shaped loop extending over 2 - 4 Mpc. The surface brightness of this emission, which appears to coincide with some galaxies at redshifts belonging to the Coma supercluster. The equipartition magnetic field required to produce the observed level of synchrotron brightness is also of order 0.1 - 0.2 μG, in intergalactic features extending over 3 - 4 Mpc. We are currently attempting an improved 74MHz image over a 15° field (Kronberg, Enßlin, Perley, Kassim and Cohen (work in progress)).

More recently, Bagchi *et al.* (2002) have deduced similar intergalactic magnetic field strengths of 0.3 - 0.5 μG in a region of apparently diffuse intergalactic emission around the cluster ZwCl 2341.1+0000 at z$\sim$0.3. They attribute the diffuse synchrotron emission to *in situ* heating by acceleration by large scale intergalactic accretion flows. They compare their results with simulations by Miniati *et al.* (2001a,b), in which CR electrons are accelerated at the locations of baryonic shocks as the intergalactic gas accretes in the pre- cluster formation stage in LSS evolution. This type of process probably works synergistically with galaxy outflow energy that we discussed above. A plausible scenario is that direct galactic BH enery output produces the primary source of IGM electron CR acceleration, and intergalactic accretion shocks are a secondary process that re-energizes these pre-seeded (by galaxies) IGM magnetic fields.

5 Intergalactic magnetic fields at earlier epochs

Given the limitations of space here I shall briefly relate sample observations, and the results of theoretical and modelling studies suggesting that magnetic field strengths in galaxy systems did not grow slowly, or quasi-exponentially over a Hubble time; Rather they were already at Milky Way interstellar levels up to at least 10 Gyrs ago. A more detailed examination of this question can be found in the review by Kronberg (1994). The combined analysis of Faraday rotation and optical spectroscopic data in galaxy systems at z $\approx$0.4, and z $\approx$2 both indicate B $\sim$ several μG at these epochs: They are PKS 1221-02 (Kronberg, Perry & Zukowski 1992), and 3C191 (Kronberg Perry and Zukowski 1990), respectively. Figure 4 shows the result for the latter, associated absorption line quasar at z=1.95.

The direct observational evidence is qualitatively in good accord with calculations by Furlanetto & Loeb (2001) for AGN-BH magnetization of the IGM over a wide redshift range, and by Kronberg, Lesch & Hopp (1999) for primeval dwarf galaxies (Section 2).

Other indirect, of "proxy" indicators of significant magnetic fields at early times are: (1) the growing evidence for massive BH formation at redshifts $\gtrsim$6, (2) metal lines in the high redshift (intergalactic) Ly-α forests, (3) redshifted FIR emission from dust in primeval galaxies, that presumably ties to early metal production *via* S/N, and their generation of magnetized winds and outflows that we observe in detail in the z $\approx$ 0 universe.

6 Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council of Canada. I want to specially acknowledge my colleagues Stirling Colgate, Hui Li, Quentin Dufton, Torsten

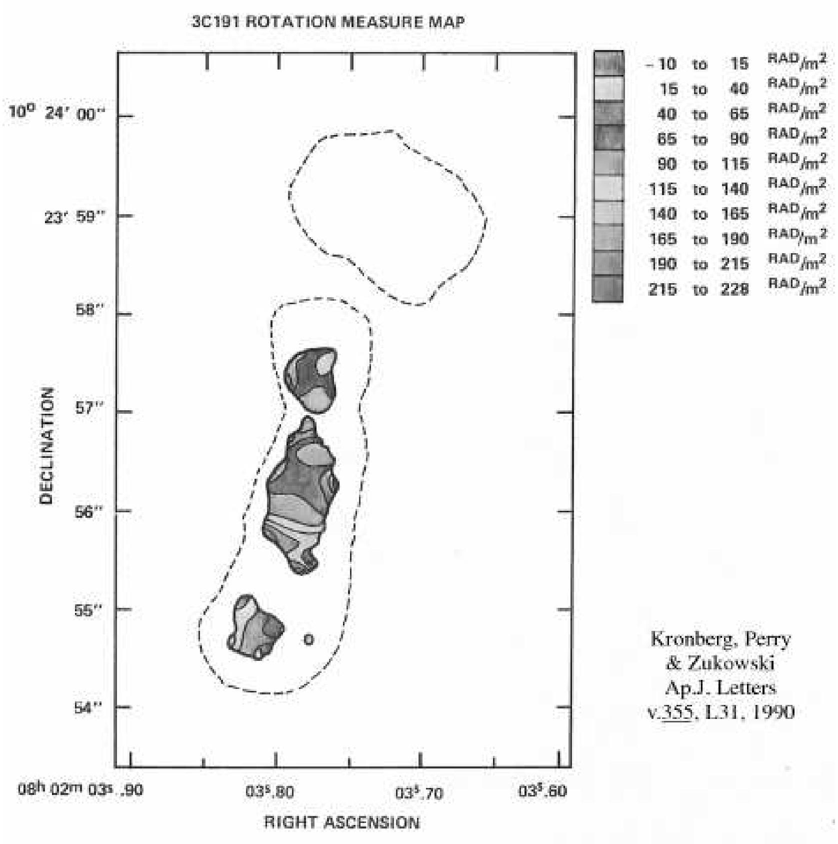

Figure 4: An image of the RM variations (in the observer's frame) along the 4 $''$- long jet of the associated absorption line quasar 3C191. The RM variations combined with the optical absorption spectrum-determined column densities give B $\sim$ 2 - 5 μG in this system at z=1.95 (reference in Figure)

Enßlin, Gabriele Giovannini, Namir Kassim, Roland Kothes, Phil Perillat, Rick Perley and Chris Salter who are participating in various projects summarized in this paper.

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