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NEW PROBES OF INTERGALACTIC MAGNETIC FIELDS BY RADIOMETRY AND FARADAY ROTATION

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ABSTRACT

The energy injection of galactic black holes (BH) into the intergalactic medium via extragalactic radio source jets and lobes is sufficient to magnetize the IGM in the filaments and walls of Large Scale Structure at $< |B| > \sim 0.1\mu$G or more. It appears that this process of galaxy-IGM feedback is the primary source of IGM cosmic rays(CR) and magnetic field energy. Large scale gravitational infall energy serves to re-heat the intergalactic magnetoplasma in localities of space and time, maintaining or amplifying the IGM magnetic field, but this can be thought of as a secondary process. I briefly review observations that confirm IGM fields around this level, describe further Faraday rotation measurements in progress, and also the observational evidence that magnetic fields in galaxy systems around z=2 were approximately as strong then, ∼10 Gyr ago, as now.

Key words : cosmology: large scale structure – extragalactic radio astronomy – synchrotron radiation

I. INTRODUCTION

The enormous energy release of black holes(BH), and their consequent ability to return energy into the intergalactic medium raises the obvious question of whether this distributed energy can be detected beyond galaxy clusters. The fact that a significant fraction of the BH-ejected energy is in the form of CR and magnetic energy 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 by hot intergalactic gas, or as absorption by intergalactic gas. Detections of the WHIM are also beginning to be made (Refer to the contribution by P. Henry in this volume).

Detections of low level, intergalactic synchrotron radiation have been made since the late 1980's: Kim *et al.* (1989) at 326 MHz, Kim *et al.*(1990) at 408 MHz, Enßlin *et al.*(1999) at 75 MHz, Bagchi *et al.* (2002) at 320 MHz, and Deiss *et al.* 1997 at 1.4 GHz.

In this contribution I illustrate some of these measurements, and briefly describe new, lower level radio searches that are currently underway over larger intergalactic volumes, with improved radiometric precision and sensitivity. We will briefly review calculations that show why we should see such widespread, diffuse non-thermal emission at some level. Such measurements may be of great importance for understanding the evolution of large scale structure in the Universe, and ultimately the origin of intergalactic magnetic fields.

II. SOME OBSERVATION-BASED CALCULATIONS OF GALAXY-IGM FEEDBACK ENERGY

(a) QSO-Era BH Energy Release Hased on Photon Output

The average density of galactic black holes during the "quasar epoch " has been estimated as

$$\rho_{\rm BH} \sim 2.2 \times 10^5\ {\rm M}_\odot\ {\rm Mpc}^{-3} \qquad (1)$$

This estimate, following Soltan (1982), Choksi and Turner (1992), and Small and Blandford (1992) is based on the observed global *photon* output from QSO's, and assumes that a fraction ϵ_R ∼0.1 of the BH infall energy is converted to light. It is consistent with 50% of the BH mass density having accumulated by $z = 2$. Following Kronberg *et al.* (2001) we assume that a similar fraction ϵ_B of the energy is released in the form of magnetic fields, and also that a fraction ϵ_{RL} of all QSO's is radio loud, and convert equation (1) into an average IGM magnetic field energy density at z = 2, assuming a homogeneous universe (no walls & filaments).

$$e_{\rm B} \approx 5{\times}10^{-3}\left(\frac{\epsilon_{\rm RL}}{0.1}\right)\left(\frac{\epsilon_{\rm B}}{0.1}\right)\rho_{\rm BH} \approx 7.3{\times}10^{-17}\ {\rm ergs/cm}^3\ , \qquad (2)$$

The equivalent magnetic field strength is ∼4× 10^{-8}G. Now defining a filament/void volume fraction of the IGM as $f_{filament}$, and setting $f_{filament} = 1\%$ the IGM field strength estimate for the filaments becomes ∼4× 10^{-7}G. Interestingly, the energy density for homogeneous universe is of comparable order to a global estimate of the thermal pressure of the IGM at $z \approx 2$,

$$p_{\rm IGM} \approx 1.6 \times 10^{-16}\left(\frac{n_{-4}}{10^{-4}}\right)\left(\frac{T_4}{10^4}\right)\ {\rm ergs/cm}^{-3}\ . \qquad (3)$$

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(Kronberg *et al.* 2001). This suggests that, if the entire RLQSO magnetic field energy output were uniformly spread out throughout intergalactic space, the IGM would have a plasma $\beta = p_{\rm IGM}/e_B$ near unity, *i.e.* having comparable thermal and magnetic pressures.

(b) BH Energy Release to the IGM in the Low -z Universe

We can make an analagous calculation of the global energization of the IGM at more local cosmological epochs. Sidestepping the BH photon output (above), we instead combine the BHs' dynamically estimated masses (Tremaine *et al.* 2002), low z bright galaxy surveys, and $E_{\rm infall}$ (below).

$$E_{\rm infall} = M_{BH}c^2 = 1.8 \times 10^{62} \frac{M_{BH}}{10^8 M_\odot} {\rm ergs} \qquad (4)$$

To this information we combine radio observation-based estimates of the energy that is fed into radio source lobes from their parent BH. Local universe co-moving values of ρ_{BH} are comparable to those in equation (1). 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. Even then, they do not directly reveal *all* of the energy released by the BH, that is, the GRGs' energy content in CR's and magnetic fields will understate by an uncertain factor the real aggregate energy that a central BH produces in relativistic particles, magnetic fields PdV work, etc. Further discussion on this point can be found in Kronberg *et al.* (2001) and in my other paper in this volume.

Combining $\rho_{\rm BH}$ with (4) gives an average total IGM energy density asuming 100% conversion efficiency from gravitational energy, which is $e \sim 10^{-14}$ erg/cm^3, scaled to an average BH mass of $10^8 {\rm M}_\odot$. Note that this average applies to the entire i.g. volume, including voids and galaxy filaments.

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 $(\epsilon_{\rm B})\times({\rm f}_{filament})^{-1}\times({\rm f}_{RG})$, where $\epsilon_{\rm B}$, is the fraction of BH energy released by the host galaxy as magnetic energy, and ${\rm f}_{RG}$ 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 1GHz.

For the purpose of simple global estimates I assume that $\epsilon_{\rm B}={\rm f}_{filament}={\rm f}_{RG} = 0.1$. This gives an estimate $e_B \sim 10^{-15}$ erg/cm^3, and a corresponding ${\rm B}_{IGM} \sim 1.6\times10^{-7}$G. This number is compatible with that in the previous section.

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 in these papers for the galaxy filaments is of comparable order. This is consistent with energy reservoir calculations, in that the gravitational infall energies in LSS and galaxy formation appear to be of similar order to those based on equation (4). Actual computation of magnetic field strengths at later cosmological epochs is as challenging as it is rewarding. It must include full 3-D simulations of LSS evolution that include all the magnetic field amplification processes, gas cooling, etc.

(c) Expectation Levels of Galaxy-Produced IGM Magnetic Field Strengths

Both approaches above to estimating a typical intergalactic magnetic strength in the walls and filaments of galaxies give us reason to expect $\gtrsim$0.1-1 μG fields in LSS galaxy filaments at the current epoch. In the following I describe some low-level radiometry measurements that are beginning to reach synchrotron radiation surface brightness levels that correspond to widespread 0.1 - 1 μG intergalactic magnetic fields.

III. OBSERVATIONS THAT TEST FOR FAINT INTERGALACTIC MAGNETIC FIELDS

The first firm detection of diffuse synchrotron radiation beyond galaxy clusters was obtained by Kim, Kronberg, Giovannini and Venturi (1989), using 326 MHz imaging of a 3 ° area around the Coma cluster of galaxies. Their image is shown in Figure 1. It has an rms noise level of 1.1 mJy/beam and a resolution of $2'$ EW × $4'$ 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 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 1, 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 $\sim 75\lambda$. This is evident in a negative "bowl" which is difficult to see in Fig. 1, 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 includ-

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

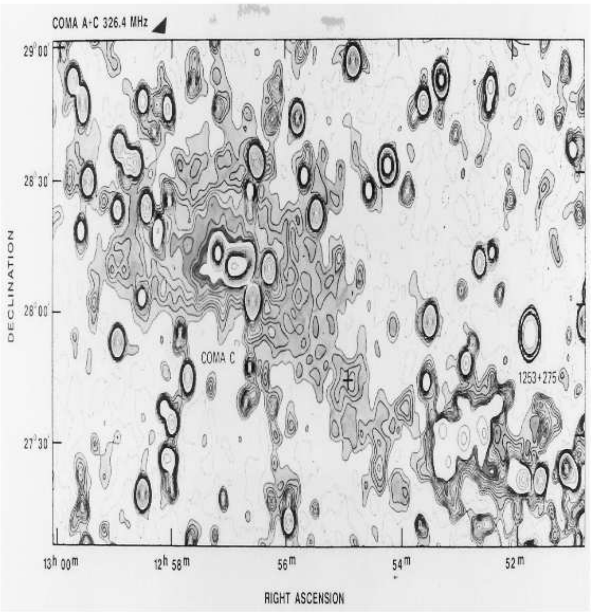

Fig. 1.— WSRT 324 MHz image of a 2.5° × 2.5° field centered slightly south and west of the Coma cluster. The image was made from a combination of 6 12-hr WSRT sessions, each with a different setting of the moveable telescopes for optimum uv-coverage. The rms noise level was 1.1 mJy/beam, and the beam size in this image is 2′ EW × 4′ NS.

ing more recent all-configuration VLA observations at 0.3 GHz. Another "ingredient" of this new 0.3 GHz image, shown in Figure 2, is a combination of the WSRT data that produced Fig. 1 with the new all-configuration VLA data. A WSRT - VLA combined image is shown at higher resolution (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 2005).

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)).

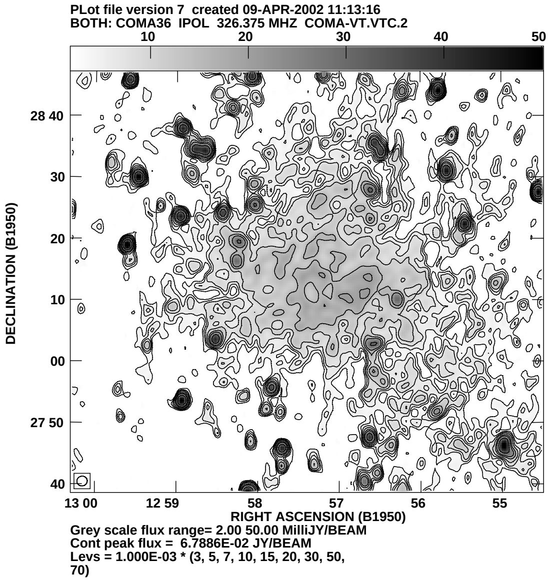

Fig. 2.— A preliminary, combined VLA-WSRT Coma cluster 0.3 GHz image of a smaller field than in Figure 1, but at higher resolution, showing the small scale structure in the Coma cluster's radio halo and its extra-cluster extensions. (Kronberg, Perley, Kassim, Giovannini and Cotton, in prep, 2005)

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 (Figure 4). They attribute the diffuse synchrotron emission to heating by *in situ* acceleration by large scale intergalactic accretion flows, and have compared their results with simulations (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.

IV. SEARCH FOR FARADAY ROTATION IN LARGE SCALE STRUCTURE

The relatively large angular size of the local superclusters (Virgo, Coma, Hercules, etc.), and the sub- μG - level magnetic fields mentioned above invites the possiblity of detecting Faraday rotation due to large scale supercluster intergalactic filaments. Unambiguous detection of intergalactic Faraday rotation is challenging due to the difficulty in separating its contribution from galactic foreground Faraday rotation, which is on comparable angular scales. The advantage of detecting RM

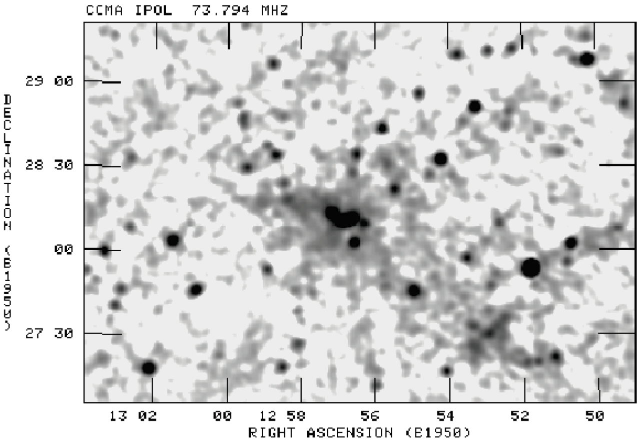

Fig. 3.— The central portion of a 74 MHz VLA all-configuration image around the Coma cluster, adapted from Fig. 3 of Enßlin *et al.* (1999). Faint intergalactic emission can be seen up to ~4 Mpc beyond the Coma cluster core. The resolution is 3.3 ′.

over IGM synchrotron "glow" lies in its potential to test for the *sign coherence* of these field sructures.

At Los Alamos we have begun to test for an RM counterpart to local superclusters. Due to the difficulties just mentioned, the results are not definitive, but I show a preliminary look at attempts in progress, by Yongzhong Xu, Salman Habib, Quentin Dufton and myself. Figure 5 shows a plot of measured RM's in the direction of the Hercules supercluster, where the galactic foreground RM is relatively modest. The aim is to correlate a smoothed RM with an estimate of the column density of supercluster filament gas, as derived from galaxy/redshift counts. The expected level of RM is comparable to that seen around the environments of GRG's, which have similar régimes of dimension and thermal gas densities. Restating equation (2) of my other article in this volume,

$$\frac{\Delta\chi}{\Delta\lambda^2} = 0.81 \times 10^6 \cdot \frac{n_{th}}{cm^{-3}} \cdot \frac{B_\parallel}{\mu G} \cdot \frac{L}{Mpc} radians/m^2 \quad (5)$$

we see that for pathlengths of a few Mpc, and ignoring the effects of field reversals, RM's at the level of a few rad/m^2 might be expected. Figure 5 shows an inconclusive result, but it illustrates that current observational data is close to being capable of seeing a RM in supercluster-scale IGM.

The existence of μG-level magnetic fields at cosmological epochs near z=2 is illustrated by the associated absorption line quasar 3C191 (see figure 6). The absorption line system in 3C191's optical spectrum shows a high ionized hydrogen column depth *close to* the quasar's redshift - i.e. in this case not in a galaxy at some intemediate redshift. Although the nature of this quasar-associated system is still not understood, the remarkably high RM's of order 2000 rad/m^2 in the quasar's reference frame lead to magnetic field strengths of a few microgauss (Kronberg, Perry, and Zukowski 1990). This is one of the first indications, since confirmed in other high z - high RM extended radio sources, that galaxy systems by z ~2 had magnetic field strengths that are similar to present epoch galaxy systems.

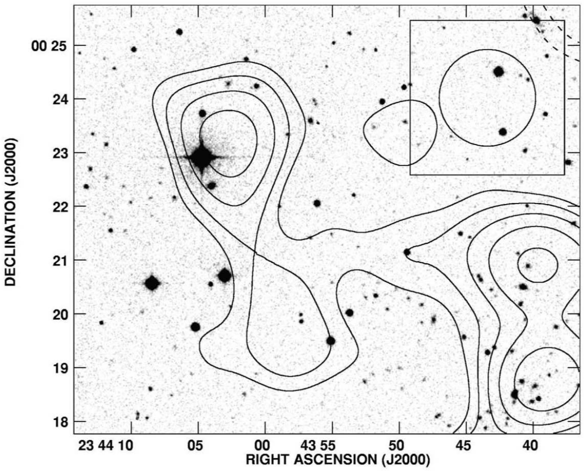

Fig. 4.— A VLA 320 MHz image around the Zwicky cluster ZwCl 2341.1+0000 at z~ 0.3 by Bagchi *et al.* 2002. The beam size (upper corner) is 1.8 ′, similar to that in the Kim *et al.* (1989) image in Fig. 1. The rms noise level is 2.5 mJy/beam, and the contour levels are at 4, 5.5, 8, 11.25.. mJy/beam.

V. SUMMARY

I have summarized clear evidence that magnetic fields in the local universe exist on scales beginning at those of galaxy clusters, and extending to several Mpc. Their energy content can be understood as feedback energy of galactic black holes through the formation of radio jets and lobes over a Hubble time. The primary CR acceleration mechanism, for which radio lobes are the prime laboratories, must be very efficient, as required by the energetics of the largest radio sources (Kronberg *et al.* 2001). This could be magnetic reconnection on large scales, a process we are only beginning to understand, or some other highly efficient process that can occur on large scales (Kronberg *et al.* 2004). Some BH-seeding of intergalactic magnetic fields has certainly also come from primeval galaxy star- and S/N-driven outflows at z$\gtrsim$7. It will also have been provided by cosmologically early massive BH's, which appear to have begun forming nearly a Hubble time ago. Both of these processes have been shown capable of seeding a significant fraction of the IGM at earlier cosmological epochs (Kronberg *et al.*, 1999, Furlanetto & Loeb, 2001). The current-epoch magnetic levels can also be reproduced in simulations, in which IGM magnetic fields from earlier "seedings" can be amplified in large scale infall shocks of LSS. It seems that both processes, galaxy BH feedback, and large scale gravitational infall energy can produce in-

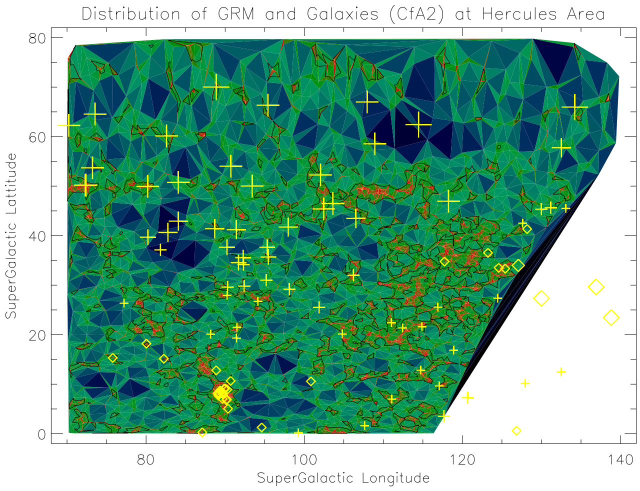

Fig. 5.— An preliminary intercomparison, on supergalactic coordinates, of Faraday rotation measures and galaxy surface density in the Hercules supercluster. Optical data are taken from the CfA2 Survey. The crosses indicate positive RM's, and the diamonds are negative RM's. The size is proportional to RM magnitude (Xu, Kronberg, Habib and Dufton, work in progress).

tergalactic magnetic fields to the levels required to produce the synchrotron radiation we are seeing. The most direct observational verification comes from the galaxy BH feedback scenario. The former can be thought of as a primary mechanism, and the latter as a secondary process that amplifies intergalactic fields in the sense that the ultimate origin of intergalactic magnetic fields was originally "feedback" from stars and galaxies, combined with a possible primeval pre-stellar epoch origin.

I briefly describe attempts in progress to detect Faraday rotation from intergalactic magnetic fields embedded in local large scale structure, and have presented representative evidence to show that present epoch-level interstellar field strengths existed in galaxy systems at z$\gtrsim$2 or cosmological lookback times $\gtrsim$ 10 Gyr.

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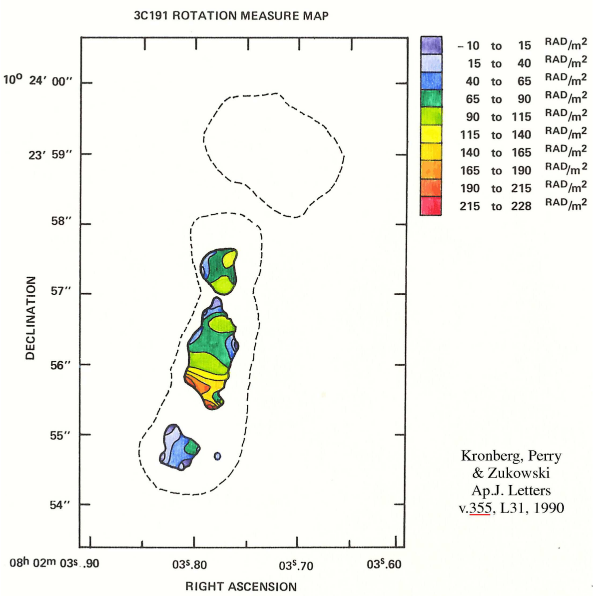
REFERENCES

Bagchi, J., Enßlin, T. A., Miniati, F., Stalin, C. S., Singh, M., Raychaudhury, S., & Humeshkar, N. B. 2002, New Astronomy, 7, 249



Kronberg, Perry & Zukowski Ap.J. Letters v.355, L31, 1990

Fig. 6.— An image of the RM variations along the 4 ″-long jet of the associated absorption line quasar 3C191. The combination of the RM variations and absorption spectrum-determined column densities give B $\sim$ 2 - 5 μG in this system at z=1.95

Chokshi, A., & Turner, E. L. 1992, MNRAS, 259, 421

Deiss, B. M., Reich, W., Lesch, H., & Wielebinski, R. 2003, A&A, 321, 55

Enßlin, T. A., Kronberg, P. P., Perley, R. A., & Kassim, N. E. *Diffuse Thermal and Relativistic Plasma in Galaxy Clusters, MPE Report*, eds. Böhringer, H. Feretti L., & Schuecker P. 1999, 271, 21

Furlanetto, S. R., & Loeb, A. 2001, ApJ, 556, 619

Kim, K. T., Kronberg, P. P., Giovannini, G., & Venturi, T. L. 1989, Nature, 341, 720

Kim, K. T., Kronberg, P. P., Dewdney, P. E., & Landecker, T. L. 1990, ApJ, 355, 29

Kronberg, P. P., Dufton, Q. W., Li, H., & Colgate, S. A. 2001, ApJ, 560, 178

Kronberg, P. P., Colgate, S. A., Li, h., & Dufton, Q. W. 2004, ApJ, 604, L77

Kronberg, P. P., Lesch, H., & Hopp, U. 1999, ApJ, 511, 56

Kronberg, P. P., Perry, J. J., & Zukowski, E. L. H. 1990, ApJ, 355, L31

Miniati, F., Ryu, D., Kang, H., & Jones, T. W. 2001a, ApJ, 559, 59

Miniati, F., Jones, T. W., Kang, H., & Ryu, D. 2001b, ApJ, 562, 233

Ryu, D. S., Kang, H. S, & Biermann, P. L. 1998, A&A, 335, 19

Ryu, D. S., Kang, H. S., Hallman, E., & Jones, T. W. 2003, ApJ, 593, 599

Small, T. A., & Blandford, R. D. 1992, MNRAS, 259, 725

Soltan, A. 1982, MNRAS, 200, 115

Tremaine, S. D., *et al.* 2002, ApJ, 574, 740