OBSERVING MAGNETIC FIELDS ON LARGE SCALES

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ABSTRACT

Observations of magnetic fields on scales up to several Mpc are important for understanding cluster and large-scale structure evolution. Our current census of such structures is heavily biased – towards fields of several μG, towards fields in deep potential wells, and towards high inferred field strengths in cooling flow and other clusters from improper analysis of rotation measure data. After reviewing these biases, I show some recent results on two relics that are powered in very different ways. I describe new investigations that are now uncovering weak diffuse fields in the outskirts of clusters and other low density environments, and the good prospects for further progress.

Key words : acceleration of particles – clusters of galaxies – cosmology: large scale structure – magnetic fields

I. INTRODUCTION

Studies of diffuse extragalactic magnetic structures – those not clearly associated with parent AGNs – have reached a level of sufficient maturity that it is time to review what we've seen and what we might have missed. I will start by examining the observations in the phase space of magnetic field strength and angular size [B,θ]. After using this to discuss some of the inherent observational biases in magnetic field studies, I will highlight three different types of diffuse structures of current interest - cluster-wide fields probed through rotation measures, energization of cluster "relic" sources, and diffuse sources seen in weak potential wells.

II. [B,θ] PHASE SPACE

Figure 1 introduces [B,θ] space where we can look at a) known objects, b) benchmark fields that would be pressure matched with cosmological structures, and c) selection effects and other biases. The exact placement of features on this diagram is not important at this stage – increasing angular size generally reflects physically larger structures. However, since the selection effects depend only weakly on redshift, [B,θ] space is a useful place to start our investigation.

Beginning with the observations, we note that most information about magnetic field strengths comes from minimum energy estimates (B$_{min}$) – *i.e.,* the field strength that minimizes the total energy in the relativistic plasma under the constraint of the observed synchrotron luminosity. This closely approximates the field strength that yields an equipartition in energy between fields and relativistic particles. Readers are cautioned to distinguish such field-particle equipartition from other uses of the term, such as the equipartition

of pressure between relativistic and thermal plasmas.

At the small, high field (pressure) end, we find the hot spots of powerful radio galaxies and quasars –these are transient features associated with jet-driven shocks, pressure balanced on average by the ram pressure of their advance into the local thermal medium. In clusters of galaxies, we find larger scale tails and bridges of emission associated with AGN outflows. These diffuse structures presumably move only slowly through their local medium and are therefore approximately in static pressure balance. However, the minimum pressure estimates often fall below those of the surrounding medium (e.g., Morganti et al. 1998; Worrall & Birkinshaw 2000), so additional sources of pressure are needed. At even lower minimum energy fields, we find the radio "relics", discussed further below and in these proceedings in more detail by G. Giovannini. Cluster-wide halos, as discussed here by L. Ferretti, have minimum energy or inverse-Compton estimated field strengths in the range 0.1 - 1 μG. I have not included in the [B,θ] diagram the 1-35 μG rotation measure estimates of cluster fields (Carilli & Taylor 2002) since I do not believe they are supported by the observational evidence.

Two "benchmark" field strengths/pressures are indicated – those associated with the thermal pressure in clusters of galaxies, which range over an order of magnitude across a cluster (e.g. Briel, Fignogeunov & Henry, 2004) and pressures characteristic of the WHIM (e.g. Nicastro 2003). Eventually, when the scaling relationships are better understood for these pressure benchmarks, it would be useful to show their θ dependence (perhaps at different redshifts) on the [B, θ] diagram.

This now brings us to the question of observational constraints – the main reason for constructing the [B, θ] diagram. The first constraint is provided by the *maximum lifetime field* (B$_{\tau max}$)- the field strength which maximizes the radiative lifetime of emission *at a fixed observing frequency.* Ignoring Coulomb losses, which

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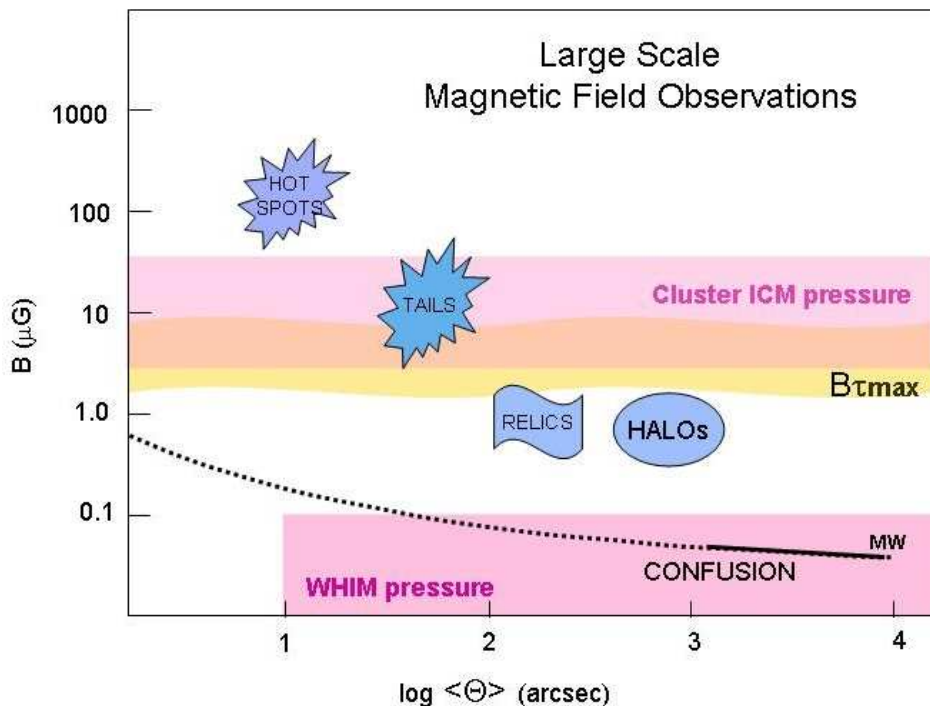
Fig. 1.— [B,θ] space - a perspective on observed structures, pressure-equivalent benchmarks, and observational constraints. The curved dashed line towards the bottom represents the confusion limit, irreducible in the large angle (solid line) portion due to the Milky Way.

are unimportant in the radio regime for diffuse synchrotron sources, and assuming an initial power law spectrum of -0.5, $B_{\tau max} = 3.2\ (7.1)\ \mu G$ at $z = 0\ (0.5)$, corresponding to lifetimes of $10^{8.3\ (8.0)}$ years. At field strengths a factor of ≈ 4 from $B_{\tau max}$, the lifetimes drop by a factor of two. A maximum lifetime field exists because if the field were higher, synchrotron losses would reduce the lifetime, and if the field were lower, synchrotron emission at a given observational frequency would come from higher energy particles, whose inverse Compton losses would again reduce the lifetime. Curiously, the maximum lifetime *field strength* is independent of observing frequency (although the lifetime itself is frequency dependent).

The *maximum lifetime field* is closely related to the *maximum lifetime particle energy* ($E_{\tau max}$), as discussed over the years and described in the tutorial by Sarazin (1988). The distinction between the two is important: $B_{\tau max}$ tells you what strength fields containing a fixed population of particles will be observed for the longest times; it thus forces an observational selection bias as shown in Figure 1. $E_{\tau max}$ tells you the energy and lifetime of the longest lived relativistic particles, which can later be re-energized to become visible at radio frequencies. This visibility depends on the re-energization and the local current magnetic field strength, and provides a different set of model-dependent selection effects. This paragraph is worth re-reading.

The second critical observational constraint is related to "confusion" levels (Condon, 1974). To study very low surface brightness features, one typically wants to work at low resolution, approximately on the angular scale of the target source. If the observations are sensitive enough, the fluctuations in the background due to the combined flux of sources within one "beam" then become dominant. In Figure 1, I have indicated this confusion limit in terms of its equivalent magnetic field strength (B_{min}), assuming an equal contribution from relativistic particles at each angular scale (as opposed to physical scale). This is a useful approximation, because the redshift dependence of B_{min} is only $z^{2/7}$ at a fixed confusion flux limit and a fixed angular scale.

Unfortunately, this confusion limit is right in the regime where relativistic plasmas in pressure equilibrium with the WHIM would become visible. Attempts to push below the confusion are described below, although at sufficiently large angular scales $\geq 1^o$, the irreducible confusion from the Milky Way will become dominant.

III.   ROTATION MIS-MEASURES

Since there are widespread magnetic fields and thermal plasmas in clusters of galaxies, at some level their resulting Faraday rotation will be seen. However, the evidence to date that observed rotation measures are
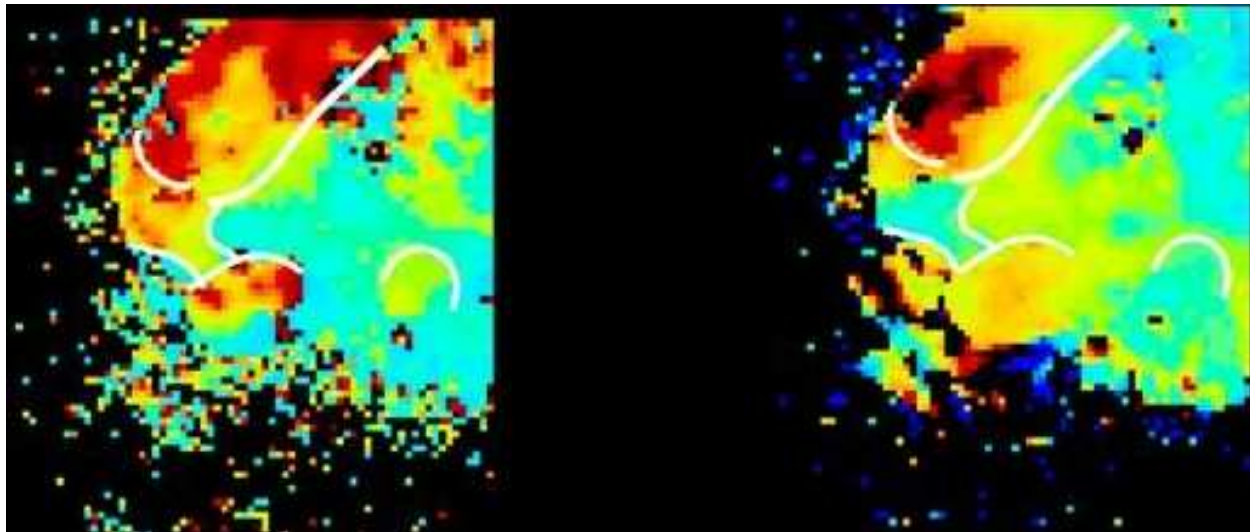
Fig. 2.— Polarization of the eastern lobe of Cygnus A, original and derived maps kindly provided by C. Carilli & R. Perley – these maps were derived from multifrequency data at 3.7cm using the VLA. Left: Magnetic field orientation, color coded; Right: Rotation Measures (arbitrary color scale). Hand-drawn white lines indicate positions where rapid shifts in magnetic field direction are accompanied by rapid shifts in Rotation Measure – an unambiguous signature of rotation measure *local* to the source, not due to any intervening cluster field.

due to cluster wide fields (with magnitudes of 1-35μG, Carilli & Taylor 2002) is on quite shaky grounds.

There are two types of cluster rotation measure studies. In the first, rotation measure variations across an individual cluster radio source are used to infer cluster-wide fields. Rudnick & Blundell (2003) discuss the numerous problems with this inference, and argue that a plausible alternative is that the rotation measures arise in a thin thermal skin mixed with the radio source's own relativistic plasma. An excellent example of this effect is shown in Figure 2. Here we see the polarization angle structure of the eastern lobe of Cygnus A (which must be intrinsic to the source) and the corresponding rotation measure structure (see Perley & Carilli 1996). It is obvious that many patches of rotation measure correspond to coherent patches of Cygnus A's own magnetic field – *not* some random foreground cluster screen. Until such effects are eliminated from maps of individual sources (and there is no way presently to do so), one cannot infer cluster-wide fields from such observations. The demonstration that certain cluster-wide field geometries *might* explain variations across *some* sources (Ensslin et al. 2003) falls quite far short of demonstrating that cluster fields are actually responsible for observed rotation measures.

The second line of evidence claimed for cluster-wide fields is the larger dispersion of rotation measures for distant background sources seen through clusters than for control samples not seen through clusters. While in principle this method could work, the studies to date are seriously flawed (see Rudnick & Blundell, 2004).

An example of a flawed statistical study is shown in Figure 3. The claims for an excess rotation measure in the direction of the Coma Cluster (Kim et al. 1990) are based on what appears to be a statistically signifi-

cant excess near the cluster center. Unfortunately, the sample contains many sources that are actually in the cluster itself (a demonstrably dense environment with distinct types of radio sources) as opposed to the control sample of background radio sources. This flaw in the experimental design must be corrected by removing actual cluster sources from the sample. In addition, there are multiple serious apparent errors in the actual data analysis. 5C4.70, for example, with an 18cm polarization percentage of 0.9±0.7 (a non-detection) leads to only a 5° error in polarization angle (Kim et al. 1994), and then to a highly accurate quoted rotation measure in Kim et al. (1990). Similarly, 5C4.112b has a reported 21cm polarization percentage of 0.9±1.0 (a non-detection) a polarization angle error of 10° and another high quality quoted rotation measure. The results of eliminating cluster sources and re-calculating errors is shown in Figure 3 for the Kim et al. work. It is obvious that the Coma cluster magnetic field, known for decades through its synchrotron halo (e.g., Willson 1970), shows no measureable rotation measure effect at present levels of sensitivity.

At this meeting, T. Clarke and M. Johnston-Hollitt each defended the statistical studies. Clarke presented revised data from Clarke, Böhringer & Kronberg (2001), by appropriately dropping the sources actually embedded in clusters. However, to improve the now poor statistics, she added data from the literature of questionable quality (e.g., unmatched spatial resolution, errors in data analysis) such as noted above from Kim et al. (1990). Johnston-Hollitt showed the results from a new southern hemisphere survey; her analysis is necessarily complicated since the sources are spatially resolved. However, there is no control sample, no off-cluster sources that are observed and processed in the
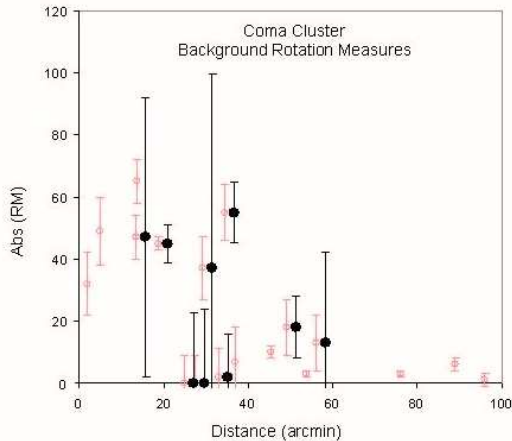
Fig. 3.— Rotation Measures of radio sources in the direction of the Coma Cluster from Kim et. al 1990 (red). The same data (offset for clarity), but including only actual background sources, and showing the correct errors (black). No cluster RM effect is visible in the corrected data.

same way, so it is not possible to draw any conclusions about clusters from this work.

There thus remain no reliable measurements of cluster-wide fields from rotation measure studies at present. With a large investment of time, it might be possible to do this background source experiment properly using the Very Large Array. Otherwise, the SKA offers the most promise.

IV. RELICS

Studies of these patchy cluster sources without an obvious parent AGN have reached the point that they can be classified into physically meaningful categories (see Kempner et al. 2003). They distinguish between:
a) "AGN Relics" (<100 kpc) which may actually show connections to a nearby AGN when deep maps are available, and are likely associated with bouyant bubbles and dredged up thermal material from the parent cD core, and
b) "Radio Phoenix" structures on larger scales, which are presumed to illuminate relativistic plasma from previous radio galaxy activity, currently recompressed and reaccelerated by merger or other shocks; and
c) "Radio Gischt" - thin relics up to several Mpc long on the periphery of clusters, resulting from either merger or accretion shocks.
In these proceedings, a nice overview of relic properties, with a somewhat different classification scheme, is presented by G. Giovannini.

In this paper, I present initial spectral studies of one AGN Relic and one Radio Phoenix from the thesis work of A. Young. The purpose of these studies is to uncover the acceleration processes that provide the initial population of relativistic electrons.
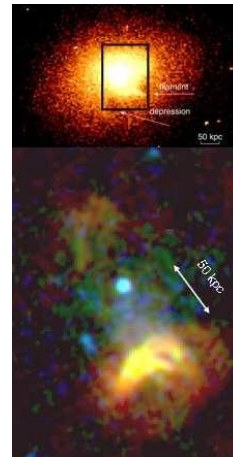
Fig. 4.— Top: Chandra (XMM) image of the inner 200 kpc of the MKW3s cluster, centered on the cD (from Mazotta et al. 2002). The box indicates the approximate region shown in radio emission at the bottom, from multi-frequency VLA maps) color coded by spectral index, with red=steep (Young et al. 2004).

(a) An AGN Relic

The MKW3s system is shown in Figure 4. The X-ray emission shows a bright finger of emission emerging to the Southwest, extending out over 50 kpc from the core. The temperature of this plasma is considerably lower (by 2-3 keV) than the surroundings, and is fairly well aligned with the radio structure. The bright steep-spectrum filamentary emission at the Southwest terminus of the radio source was seen in the FIRST survey (Becker, White & Helfand 1995), but its origin was unclear (Mazzotta et al. 2002). These new deep observations, at 90, 20, and 6cm on the VLA* find a bridge of emission leading back through an AGN core and extending to another faint steep-spectrum feature at the northern terminus.

The original filamentary radio source, which previously could have been thought of as unpowered "relic" emission, has therefore been transformed into a radio galaxy type structure, albeit a most curious one, with extremely steep ($< -3.5!$) spectra at its bright end. Physically, it must have a different origin than the "relaxed doubles" or the tailed cluster radio galaxies that fade and steepen away from the nucleus. It must also have a different origin than jet driven high luminosity doubles that have bright flat spectrum regions at their terminus. Nor is it simply a bouyantly rising detached bubble, since there is an AGN and a continuous bridge of emission.

This radio/X-ray system is very similar to that of Abell 133 (Fujita et al. 2002), although the structure of the diffuse emission is not yet clear. These two systems both have steep spectrum filamentary radio structures
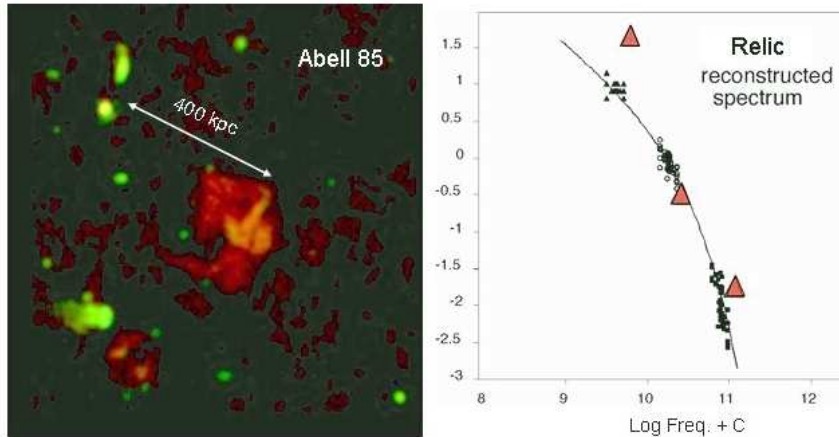
Fig. 5.— Left: VLA radio image of Abell 85 (Young et al. 2004) at a resolution of 14", with color-coded spectral indices (red=steep). Right: Reconstructed spectrum of the relic as described in the text, along with triangles showing the relative sensitivities at different VLA observing frequencies.

at the end of a cool column of thermal gas, extending $\approx 50 kpc$ from the core of a cooling flow cluster.

One possibility for these unusual physical systems is that they represent a continuous supply of energy from the AGN, but with a wider opening angle than the collimated jets often seen in radio galaxies. Such a broad flow, probably subsonic, could entrain and dredge up the cool bright finger of thermal gas, as well as accumulate a large, bright pool of relativistic particles at the terminus, strongly steepened by radiative losses. Simulations of continuously inflated MHD bubbles (Jones & De Young 2004) show that they can develop mildly supersonic flows and filamentary magnetic field structures, and may be a promising way to explain sources such as MKW3s and Abell 133.

(b) A Radio Phoenix

Abell 85 is a well-studied dynamic cluster, with multiple on-going mergers (Kempner, Sarazin & Ricker 2002; Durrett et al. 2003). The steep-spectrum radio relic (the prototype "Phoenix", Kempner et al. 2003) has been mapped by Bagchi, Pislar & Lima Neto (1998) and Slee et al. (2001). A wide field view of the cluster, showing the steep spectrum relic and flatter spectrum radio galaxies both in and projected onto the cluster is seen in Figure 5. Our multifrequency VLA observations were designed to determine the spectral shape. on a beam-by-beam basis. Although obtaining integrated spectra are much easier, and a good first step (e.g. Bagchi et al. 1998), the beam-by-beam spectra are a truer representation of the actual electron distributions because they avoid spectral smearing. Our reconstructed spectrum is shown in Figure 5. It is constructed by sliding the observations for each beam by arbitrary amounts in ($logI$ $vs.$ $log\nu$) to fit onto the spectral shape derived from a color-color analysis (Katz-Stone, Rudnick, & Anderson 1993). It has an extrapolated *low-frequency index* of -0.87, much steeper than

any other radio galaxies. One interpretation is that the relativistic electrons did not originate in a radio galaxy, but have been newly accelerated in a low Mach number shock. The spectral shape data may also be compatible with the flatter low frequency spectra of radio galaxies, if there are significant fluctuations in magnetic field along each line of sight. These possibilities are explored further in Young et al. (2004).

A very important observational lesson is also apparent from Figure 5. The triangles denote the relative sensitivities of the VLA at wavelengths of 90, 20, and 6 cm. If you consider the observed spectrum as a model source, you can slide it to any arbitrary position in $logI$ $vs.$ $log\nu$ space to determine its detectability. The important thing to note is that for a source with this amount of curvature, emission may easily be detectable at 20cm, but not at either 90cm or 6cm. Thus, one cannot rely on low frequency surveys, for example, to detect such sources, even though they have very steep spectra. Curvature in the spectrum and varying sensitivities demand that searches be conducted at a variety of frequencies.

V. UNBIASED SEARCHES FOR DIFFUSE EMISSION

(a) WENSS/WISH

Since previous searches for halos and relics have focussed primarily on clusters (e.g. Kempner & Sarazin 2001, Giovannini & Feretti 2002), we have undertaken an unbiased search of the WENSS (Rengelink et al. 1997) and WISH (the southern extension, De Breuck et al. 2002) surveys for diffuse sources (Delain et al. in preparation). The basic technique was to filter all the images from these surveys to remove the small scale structure and search the residuals, using the simple multiresolution filtering scheme described by Rudnick (2002). A wide variety of diffuse sources were found,
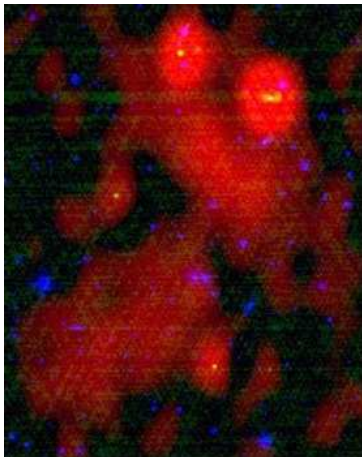
Fig. 6.— A diffuse radio source discovered in the WENSS survey (red) overlaid with the FIRST images of compact sources (yellow/green) and the Digital Sky Survey (blue).

many of them already known. These included giant radio galaxies and cluster halos and relics.

One of the newly recognized sources is shown in Figure 6 (without coordinates as we attempt to understand the optical environment). The radio structure consists of two patches of diffuse emission that extend roughly perpendicular to each other over more than 10'. There is no extended X-ray emission visible, although the SDSS shows the presence of several loose clusters or galaxy groups. This system suggests that diffuse radio sources can form outside of dense potential wells, and therefore raises questions about the mechanisms currently invoked for producing them. It emphasizes that searches for diffuse emission need to look beyond rich and/or X-ray emitting clusters.

(b)   TONS08

We are conducting another blind search for diffuse radio structures by making deep VLA maps at 90cm of the TONS08 area from the TexOx-1000 (TOOT) Project [†]. This field is being studied by others in a variety of ways, and two 100 Mpc superstructures have already been identified (Brand et al. 2003). The initial results from the new radio work are shown in Figure 7. On the left is a 36 square degree ($6^o \times 6^o$) field constructed as a mosaic of 26 individual telescope pointings. The resolution of this image, made using the VLA D configuration, is ≈ 180"; it is thus sensitive to sources much larger than can be seen in the NVSS (Condon et al. 1998). The color provides a rough measure of the spectral index (red=steep) by comparison with the NVSS survey of the same region.

To maximize the sensitivity to large scale structures we need to convolve this image to a lower resolution. This immediately takes us to the "confusion" limit discussed above and shown in Figure 1. In order to reach below the confusion, we therefore conducted the same

set of observations using the VLA B configuration, at approximately $10\times$ finer resolution, and subtracted the contributions from small sources from the low resolution data.

The result of convolving these residuals to a resolution of 420" is shown on the right of Figure 7. Approximately 90% of the flux from small sources has been removed, and we are working to improve this subtraction. Through the magic of image processing, a 1.5σ diffuse source is visible in green at the position (-0.2,-0.2). The convolved original map is shown in red; yellow regions indicate the presence of both compact sources and diffuse residuals. Given the variety of effects that produce sidelobes and other spurious structures in deep radio images, investigations such as these must be done quite carefully. However, our results so far are encouraging and we look forward to probing the lower pressure regions associated with large scale structures.
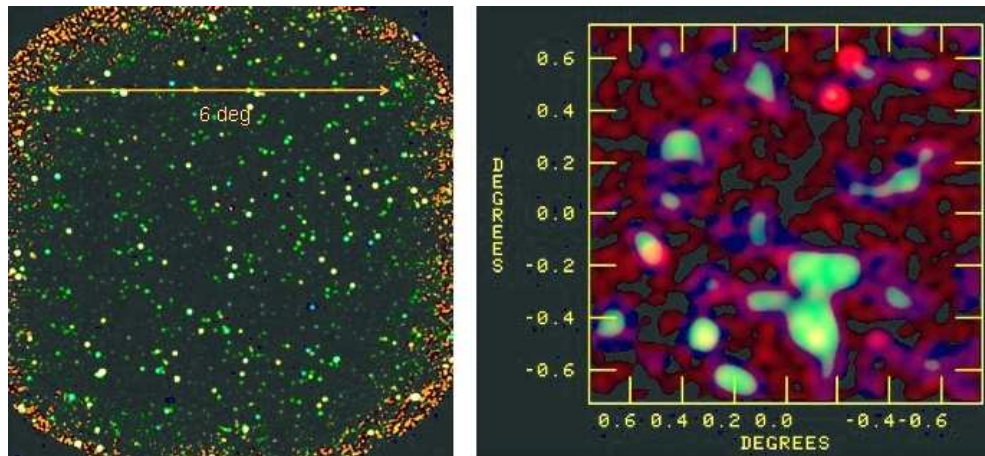
VI.   CONCLUDING REMARKS

In this paper, I have shown the limited view we have today of magnetic fields on large scales, and some of the opportunities for widening our knowledge, both with current instruments and especially with the new low frequency arrays and the SKA. It appears likely that magnetic fields can grow and relativistic particles can be accelerated under a wider range of physical conditions than currently observed. As we probe these new regimes, it is incumbent upon us to work rigorously to ensure that our observations reflect the universe, and not simply our expectations.

[†]http://www-astro.physics.ox.ac.uk/ sr/texox/toot.html

Fig. 7.— The TONS08 wide field VLA mapping at 90cm. Left: full $6^o \times 6^o$ field color coded by spectral index using the NVSS (red=steep). Right: closeup of residual emission showing possible diffuse structure in green.

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