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The Origins of Galactic Magnetic Fields

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Extragalactic Magnetic Fields in the Extragalactic Universe and Scenarios Since Recombination for their Origin

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Abstract. I briefly review recent observations, some related physics and modelling, and future possibilities relating to our knowledge of the strength, structure and evolution of extragalactic magnetic fields.

1. Introduction

Magnetic fields in wider space beyond the Solar System are among the last invisible forms of widespread energy to be measured. However their strength, ordering scales and sense (direction) require further measurements, and some of these have only recently become practical. These include observations in X-ray, radio including Faraday rotation (RM), optical UV, X-ray and γ-ray bands, and cosmic rays. It is interesting, and perhaps instructive in A.D. 2000 to note that the first interstellar magnetic field strengths were correctly deduced by Schlüter and L. Biermann (1950) to be close to 5 μG. Interesting, because they arrived at this value from physical arguments based on the energy density and isotropy of the (then newly measured) cosmic rays up to 10^{16} eV, combined with a knowledge of the thickness of the Galactic plane. Now, after 50 years of difficult astronomical measurements, the more directly measured Milky Way field strengths are converging on values remarkably close to Schlüter and Biermann's result. Cosmic rays, now seen at energies up to 10^{21}eV, may in future resume their importance – this time for probing *extragalactic* magnetic fields.

The remainder of this talk will focus on magnetic fields *beyond* galactic disks. I discuss how recent measurements, analyses and simulations are better clarifying where the μG+ level cosmic magnetic fields may have come from.

2. Magnetic Fields in Galaxy Clusters and Beyond

By using a combination of X-ray, Faraday rotation measure (RM), and radio imaging measurements, it has recently been possible to probe both the strength and approximate morphology of magnetic fields in clusters of galaxies. The first attempt at a statistical probe using RMs of background radio sources by Lawler and Dennison (1982) was later confirmed by a detailed probe of the Coma cluster (Abell 1656), the nearest large cluster to us, by Kim et al. (1990). Their estimate was $< |B| >_{\rm icm} = 2.5\ (\ell/10\ {\rm kpc})^{-1/2}\, h_{75}^{1/2}\ \mu$G for Coma's core zone and a subsequent discovery of still smaller ℓ scales down to ~ 0.1kpc (Feretti et al. 1995) raises this estimate to $\sim 7.5\mu$G.

Clusters with strong cooling flows have been similarly probed – by combining RM imaging of extended radio sources embedded within their core zones, with electron column densities, from ROSAT X-ray images. A review of results for 14 clusters by Taylor, Allen & Fabian (1999) reports field strengths ranging from $10 - 100\mu$G in the relatively dense, X-ray intense cluster core cooling flow regions. The implied magnetic energy densities are of similar magnitude to nkT for the cooling flow plasma.

Given that strong cooling flows, and strong cluster-wide synchrotron emission (as in the Coma cluster) are somewhat atypical, a recent study by Clarke, Kronberg & Böhringer (2000) produced magnetic field estimates for 16 clusters, without strong cooling flows. Their $z \leq 0.1$, $L_x \geq 10^{43}\,h_{75}^{-1}$ erg s^{-1} cluster sample has typical field strengths in the range of 5μG for cluster radii $r \leq 500\,h_{75}^{-1}$ kpc, and also a high B-filling factor. These results also produced the first global estimates of magnetic energy densities in "typical" X-ray – visible clusters – which are a significant fraction of the ICM thermal energy. Computational SPH simulations of the cosmic evolution of the ICM independently show overall consistency with these observation-derived field strengths and structures (Dolag, Bartelmann, and Lesch 1999).

Recent attempts to detect intergalactic magnetic fields *beyond* clusters have shown recent promise in imaging faint, diffuse low frequency synchrotron radiation. Such emission has been detected in areas near to the Coma cluster in the Coma - Abell 1367 supercluster zone by Kim et al. (1989) using the WSRT at 327 MHz and by Enßlin et al. (1999) using the VLA at 74 MHz ($\lambda = 4$m). They indicate $|B|$ somewhere in the vicinity of 10^{-8}G, in regions where large scale shocks may be occuring, and so may represent the "tips of icebergs" of even more widespread, and somewhat lower intergalactic magnetic fields. These recent data have opened up a new era in which LF radio and X-ray observations will be able to probe IGM field strengths beyond galaxy clusters.

3. Extragalactic Magnetic Fields that Arise in Outflow from Galaxies and Stars

An important question to ask is: "Can galaxies and stars eject enough magnetized gas into the intergalactic medium to seed a significant fraction of the IGM with magnetic fields?" If the answer is yes, and at a sufficiently early phase of the Universe when the average inter-galaxy separation was small, then the galaxies, galaxy groups, and clusters that subsequently formed will have done so out of a pre-magnetized IGM.

Two kinds of outflow from galaxies are now well recognised (cf. Rees 1987). The first is the creation by a galactic black hole/accretion (AGN) of powerful, highly collimated jets and large synchrotron-emitting clouds around a parent elliptical galaxy or quasar. However the aggregate of extended extragalactic radio sources in the Universe at $z \leq 1$ do not appear sufficient by themselves to fill a large fraction of the entire IGM. Galactic black holes that formed jets when the Universe was in a very compact state, somewhere around $z = 6$ to 10, might have been much more effective in filling large IGM volumes with magnetized plasma. An interesting investigation of this IGM seeding scenario of the IGM is described in Daly and Loeb (1990).

It has been known for many years (Burbidge 1956) that the energy content of extragalactic radio source lobes is $\gtrsim 10^{60}$ ergs, and that this enormous energy most likely comes from the gravitational binding energy of a massive collapsed object (Burbidge and Burbidge, 1965). Physical mechanisms for efficiently converting and transporting this gravitational binding energy into magnetic fields have been proposed by Colgate and Li (1999), and have also emerged from recent simulations of galactic black holes in a (rapidly rotating) Kerr metric space-time (cf. Koide et al. 2000).

The second type of outflow into the IGM arises from normal stellar processes that can eject a substantial amount of magnetized thermal and relativistic plasma at greater than their parent galaxies' escape velocity. We can calculate, and observe, that regions of intense star formation release a large amount of aggregate energy into the surrounding interstellar medium. This creates an order of magnitude or more of ISM overpressure, and so it is not surprising that regions of extreme starbursts in galaxies produce an outflow wind of the kind that we see in galaxies like M82. The outflow "halo" can be seen in radio synchrotron, optical and X-ray emission. The synchrotron and bremsstrahlung radiation, and Faraday depolarization and rotation within these outflow halos lead to estimates of the magnetic field strength and gas temperature and densities. Combined with the independently known timescales for galaxy starburst events, $\sim 10^7$ years, we can estimate the rate, per starburst galaxy, at which this outflow volume is being created globally, provided we know the galaxy density and the epoch range over which such starbursting activity occured. Kronberg, Lesch and Hopp (1999) have combined the latest data of the type described above with models of galaxy outflow back to $z = 10$, and argued that a significant fraction of the IGM in the present day Universe can be plausibly filled with magnetic fields purely by starburst outflow from dwarf galaxies in the early universe.

Apart from the above two types of large scale injection of magnetic energy in galaxies, there is increasing evidence that *individual stars* of various kinds produce outflow of gas at velocities that are comparable to, or greater than a galactic escape velocity. Examples are the polar zones of our Sun, that continuously eject gas at ~ 400 km/s, and recent evidence that a variety of stars and protostars produce collimated jets with very large outflow velocities (Feigelson & Montmerle 1999). This latter fact suggests that magnetic fields might be very effectively seeded into the wider ambient medium by stars. Another less direct early star-induced field seeding mechanism has been proposed by Gnedin, Ferrara & Zweibel (1999), in which the lumpy chaotic ionization fronts can seed early fields.

4. Discussion and Forward Look

The ideas discussed in §3 above will have given the reader an outline of how observations, difficult, scant, or not yet possible, can be combined with models of early galaxy evolution. A variety of indirect observational tests are also available to test and constrain IG magnetic fields. Examples are using (1) submillimetre imaging of highly redshifted outflow-associated FIR emission from primeval galaxies; (2) spectroscopy to study the metallicity evolution of Ly-α systems (cf. Prochaska and Wolfe 2000 and references therein) that can potentially constrain outflow scenarios of the type described in §3; (3) deep X-ray imaging that traces hot gas – an increasingly promising surrogate for intergalactic magnetic fields; and (4) extragalactic $\sim$ TeV γ rays. More detailed discussion of some of these prospects, and related ideas on high-z and early universe magnetic field generation can be found in Kronberg (1994).

If the first magnetic field seeding came from stars, as opposed to one or more of the pre-recombination scenarios proposed (and not reviewed here), then an interesting "chicken and egg" question arises if thermonuclear stellar core burning is assumed to be the prerequisite for the Biermann battery to operate inside stars to generate the first seed fields. The problem arises if the first stellar collapse to thermonuclear burning required a pre-existing magnetic field. This paradox does not arise if a seed field was produced before recombination, which may have been the case. Similarly, if the first, partially ionized, *pre*-stellar accretion disks can form from primordial, unmagnetized, pre-enriched gas, then *they* might have provided the seeding sites for the first cosmic magnetic fields.

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