

## THE ORDERING OF MAGNETIC FIELDS IN THE COSMOS

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### ABSTRACT

It is argued that the key task in understanding magnetic fields in the cosmos is to comprehend the origin of their order or coherence over large length scales in galaxies. Obtaining magnetic fields can be done in stars, whose lifetime is usually  $10^{10}$  rotations, while galactic disks have approximately 20 to 50 rotations in their lifetime since the last major merger, which established the present day gaseous disk. Disorder in the galactic magnetic fields is injected on the disk time scale of about 30 million years, about a tenth of the rotation period, so after one half rotation already it should become completely disordered. Therefore whatever mechanism Nature is using, it must compete with such a short time scale, to keep order in its house. This is the focal quest.

*Key words* : magnetic fields: creation, interstellar medium, intergalactic medium, cosmic rays

### I. INTRODUCTION

Magnetic fields in the cosmos - outside of stars - were predicted to exist around 1950, based on the observation of cosmic rays and their isotropy on the one hand, and on the linear polarization of optical stellar light. Only magnetic fields could hold cosmic ray particles in the Galactic disk, and keep them isotropic. This gave a predicted strength of  $5 \pm 1$  microGauss (Biermann, 1950). Today the best numbers for the total strength, regular and irregular component combined, give 6 - 7 microGauss (Berkhuisen quoted in Beck *et al.*, 1996).

Later, magnetic fields were indeed detected in galaxies, in clusters of galaxies and outside even, in the large scale structure (Kim *et al.*, 1989, 1990; Clarke *et al.*, 2001).

It has been demonstrated that once we understand magnetic fields in galaxies, we can fill the cosmos with magnetic fields (Ryu *et al.*, 1998; Kronberg *et al.*, 1999). Also, we think we understand magnetic fields in stars, where they are ubiquitous. The details for stars are not certain, and the magnetic fields in galaxies are not understood at all.

### II. FILLING THE ISM

It has been shown around 1950 (Biermann, 1950; Biermann & Schlüter, 1951) that in a rotating system, the non-coincidence of the surfaces of constant pressure and density drives an electric current, which cannot be compensated with an electric field due to a charge redistribution. This inevitably creates a

seed field. And so we have a magnetic field, albeit very weak, from scratch, without any requirement of a primordial field. The challenge is how to enhance this field: Two attempts found the same concept: First, in the former East Germany, Steenbeck & Krause (Steenbeck & Krause, 1965; Steenbeck *et al.*, 1966; Steenbeck & Krause, 1966; Krause & Steenbeck, 1967; Steenbeck *et al.*, 1967; Krause, 1967; Steenbeck & Krause, 1969a,b; Rädler, 1968a,b, 1969a,b, 1970; Krause, 1969), then slightly later in the US, Parker (Parker, 1969, 1970a,b,c, 1971a,b; Parke, 1971c; Parker, 1971d,e; Lerche & Parker, 1971; Parker, 1971f; Lerche & Parker, 1972; Parker, 1973, 1975a,b). In this theory a given magnetic field is twisted, raised, folded back and so enhances the given field. This argument requires both convection and rotation. So, rotating stars with convection zones could do it, even if the convection zone is deeply buried, as in upper main sequence stars. The dynamo process requires many rotation periods to operate effectively, and stars have sufficient time. Upper main sequence stars rotate typically in a few days, and live tens of millions of years, while stars like the Sun did rotate much faster in their young life, but even so, with an age of 4.5 billion years, and a rotation period of today around 26 days, there is ample time to build and enhance a magnetic field. Therefore stars can do it. Stars have winds, upper main sequence stars have rather strong and fast winds, and later explode as a supernova, while stars like the Sun have much weaker winds, and only eject some of their outer mass as planetary nebulae later. In all these winds, ejections and explosions magnetic field is injected into the interstellar medium. Therefore to fill the interstellar medium with a fairly strong magnetic field is possible and straightforward. If one adopts the point of view that blue su-

pergiant stars have a magnetic wind (Seemann & Biermann, 1997), with an Alfvénic Mach number of order a few, then the interstellar medium may have an injected power in magnetic fields of even 10 % of equipartition.

However, all this injection would produce a highly chaotic field, with structure at a few parsec at best, and so no ordered field at any larger scale, contrary to observation.

### III. ORDER

The observations show that the magnetic field in galaxies has coherent structures that have a scale of tens of kpc, winding around the galaxy, and a width of such coherent structures of order kpc, so both length scales much larger than the seed from any given single star or stellar binary system. Some authors even suggest that there is overall coherence in the sign of the regular field across the entire galaxy (Krause & Beck, 1998). These regular field structures are obviously accompanied by irregular fields, of roughly the same strength.

So we have disorder and order in the interstellar medium of galaxies. What is the time scale of injecting disorder? As already shown by Spitzer (Spitzer, 1962), and confirmed numerous times later, the typical turnover time scale of the interstellar medium is about 30 million years. This time scale is valid for heating and cooling, and it corresponds also to the pressure wave time scale, as well the Alfvénic wave time scale across the thick hot disk. However, we still need to understand the physical mechanism behind this time scale, and make sure it really applies similarly to many different aspects of the interstellar medium. It is on this time scale that the disorder is produced in the interstellar medium. Therefore the very simple observation that the magnetic field is ordered requires a powerful mechanism – a mechanism that can counteract the injection of disorder. Similar concepts should apply to clusters of galaxies.

However, before we continue this line of reasoning we need to understand the experimental and observational data that establish the strength and structure of the magnetic field in the interstellar medium as well as the intergalactic medium. We know this from synchrotron radio emission, polarization observations both of star light and of the radio emission, and from Rotation Measure data, as well as depolarization arguments. Such observations give us the numbers that believe we know, with varying, and improving levels of certainty.

In the analysis of such observations it has been commonly assumed that we have a magnetic field which is chaotic in its topology, but basically constant in strength. This led to the concept of the reversal scale, the scale on which the magnetic field component along the line of sight changes sign. Using Rotation Measure data, this specific scale enters inversely with a square-root. The smaller the reversal scale the larger the in-

ferred magnetic field, all assumed to be chaotic on the reversal scale, but with a unity filling factor. Using 1 Mpc for the visible universe as a reversal scale, but otherwise a magnetic field of constant strength led to the famous upper limit of 1 nanoGauss (Kronberg, 1994, 2000, 2001). In our Galaxy similar arguments gave a few microGauss.

However we do not really know how well the interstellar medium approximates this simple model, and we know even less for the intergalactic medium. All indications suggest a more complicated picture. The solar surface and atmosphere is another example to consider: On the sun we observe magnetic fields on scales ranging from 200 km or less, to a diameter of 1.4 million km. Solar magnetic fields are highly structured, with flux tubes and small regions (sunspots) where the magnetic field carries almost all the pressure, while on average the magnetic fields are very much weaker than equipartition.

Therefore we need to understand the effect of a turbulent magnetic field on our interpretation of the observations. The best way is to do this is to perform numerical simulations: There are several steps in this endeavour, on the one hand doing such simulations in 2D and then in 3D, and on the other hand, with only turbulence injected, but then combined with a countervailing force to impose some order. This could be shear, or an electric field such as a sheet current.

One important first step was just to “observe”, as in real life radio observations, a numerical simulation in 2D, with a magnetic field, and with power injected at various Alfvénic Mach numbers. This is what Hye-sook Lee did in the group of Dongsu Ryu (Lee *et al.*, 2003). What she found was that at a moderately high Alfvénic Mach number of injected magnetic power the magnetic field appeared very structured, just as is visible on the Sun. In “observing” such simulated configurations it becomes clear that it is easy to overestimate the overall *strength* of the magnetic field, when in fact the magnetic field is just extremely structured. This has the important consequence that the overall magnetic field strength in the interstellar medium may be lower than we think, and that recently quoted high numbers such as 6 - 10 microGauss are just representing the “islands” or filaments, and not a valid average. This means that it is possible that we might not require any further strengthening of the chaotic magnetic field beyond that injected by stars and their winds and explosions: Such sources can inject about 10 percent of the equipartition strength in the ISM! Similar reasoning might be applicable to clusters of galaxies, where the absence of regular fields within the cluster *core* might be the norm. If so the first simple step applies even better.

It seems clear that at this point it would be very helpful to perform the next steps using 3D, in which we adopt some ordering mechanism, be it shear, inverse cascading, or electric fields in the topology of a sheet,

or some other concept.

Before we move on, we need to mention the possibility of primordial fields: Are primordial fields a dominant factor, visible in the data today? If a primordial field were the ultimate origin of the ordered component of magnetic fields in galaxies today, it would have a rather regular alternation in sign from all the winding up over the many rotations since the formation of today's disk. Of course, if the primordial field were irregular on small co-moving scales, then it would just be a competitor to the injecton from stars, and much weaker than the stellar injected field due to dilution by cosmic expansion. In summary, it seems that we cannot exclude the existence of primordial magnetic fields at this time, but the data do not yet require them. Any possibly existing magnetic monopoles would also inject magnetic fields as a "dirty trail" (e.g. Wick *et al.*, 2003).

#### IV. SOURCES OF ORDER

So, in conclusion for now, this puts the challenge now on whether a mechanism can be identified to find the source of order of the magnetic field in interstellar space.

There are three mechanisms that we can think of to inject order, inverse cascading, shear and electric currents:

1) Inverse cascading. It is hard to conceive how inverse cascading, which is so to speak an infection of one magnetic field sign slowly contaminating a large region, can be so fast. We require, as noted above, a speed that corresponds to the Alfvénic time scale across the thick disk, but then for the entire galaxy. Inverse cascading is a diffusive process, and so it should go at a much slower effective velocity.

2a) Disk shear: Shear is present in almost all galaxies. However, there seem to be some where the rotation is solid body, or where at least the inner region is solid body rotation (Kormendy & Norman, 1979). But we still find regular almost circular fields! Also, shear is slow; It works at the rotational time scale and not with the hydrostatic time scale. However, there are models (Otmianowska-Mazur *et al.*, 2002), which use shear successfully on rotational time scales in a galaxy, a time scale which we suspect is an order of magnitude too slow.

2b.1) Shear in outflows: Many galaxies with very active zones of star formation and supernova explosions have vertical outflow plumes with a strongly sheared magnetic field, which is directed along the plume. (see also Birk *et al.*, 1999, 2000). If one could think of folding such plumes back into the disk in some sort of circulation system, then this might induce regularity over large scales. However, in this picture the sideways extent of the regions with regularity still need a local inverse cascade to become as large as observed.

2b.2) Shear in outflows: Based on the work in the

group of M. Urbanik we now have reason to suspect that organized outflow is a feature common to many galaxies, with evidence for visible shear at the outer boundary. Their recent observations reveal X-shaped patterns in the radio polarization in edge-on galaxies. This suggests a large scale shear, and this could enhance magnetic fields. However, again it is not clear how to obtain the large scale sign coherence from such a mechanism, and at present the resolution and sensitivity of these X-shaped features is observationally limited.

2c) Shear in inflows: Shear can occur also in inflows into clusters, as well as around contained radio galaxy tails inside clusters, both producing regular fields in the outer parts of clusters of galaxies (Kim *et al.*, 1990; Govoni *et al.*, 2004).

3) Electric currents: To encompass an entire galaxy, we need the topology of sheets, that hang/stand vertically in a galaxy; such sheets could correspond to vertical electric currents. There is the speculation that shocks might do this, in the analogy of the beach in the Bretagne; Here, a regular system of shock waves is set up in which each shock runs out of power, only to be replaced by a new shock, all caused by supernova explosions within the pattern of a spiral arm. In this particular speculation highly non-linear drifts in the magnetic and electric field in the shock push the entire hot medium to participate in a drift current, parallel to the shock surface, but perpendicular to the flow direction, (Biermann & Galea, 2003).

We have no certain solutions at this time. But a series of numerical simulations could and should illuminate the options and guide us to a correct interpretation of the observations so as to finally allow us to make some predictions, thus to test the notions developed here.

#### V. CLUES

Observations can already now give some important clues:

1) If galaxies have a regular field also in those regions where solid body rotation is prevalent, then clearly shear is not relevant. The overall torque from the general tendency of any rotating system to transport angular momentum outwards could still play a role.

2) Outflows as a source of the regularity imply that the sign of the magnetic field on opposite sides should not correlate with the sense of rotation (an important test that awaits more detailed observations).

3) Any regularity of the magnetic field in clusters of galaxies should relate to rotation, one might expect. If we, however, find very little regularity in the overall field structure within cluster core regions, then this is a perfect example of disorder destroying any order that might have been there initially.

4) If sheet currents play any role, the Sun would be an important testbed. There we can observe phenom-

ena in much more detail.

Similar and related ideas were developed by Shukurov et al. ([Beck *et al.*, 2003; Bardou *et al.*, 2001; Dobler *et al.*, 2002; Moss *et al.*, 2000; von Rekowski *et al.*, 2003; Shukurov, 2002, 2004; Soida *et al.*, 2003), and Bisnovatyi-Kogan et al. (Bisnovatyi-Kogan *et al.*, 1973).

The key at this stage lies not so much in understanding the strength, or even the disorder, but the large scale order and sign of cosmic magnetic fields.

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