ORIGIN OF COSMIC MAGNETIC FIELDS

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1 Abstract

We propose that the overlapping shock fronts from young supernova remnants produce a locally unsteady, but globally steady large scale spiral shock front in spiral galaxies, where star formation and therefore massive star explosions correlate geometrically with spiral structure. This global shock front with its steep gradients in temperature, pressure and associated electric fields will produce drifts, which in turn give rise to a strong sheet-like electric current, we propose. This sheet current then produces a large scale magnetic field, which is regular, and connected to the overall spiral structure. This rejuvenates the overall magnetic field continuously, and also allows to understand that there is a regular field at all in disk galaxies. This proposal connects the existence of magnetic fields to accretion in disks. We not yet address all the symmetries of the magnetic field here; the picture proposed here is not complete. X-ray observations may be able to test it already.

2 Introduction

Magnetic fields are found almost everywhere in the Universe, and usually they are strong, but rarely so strong as to dominate locally, as, e.g., in the environment of pulsars. After magnetic fields had been predicted to exist in the disk of our Galaxy inside the interstellar medium on the basis of cosmic ray arguments, \cite{2, 3, 27}, and the presence of optical polarization from dust scattering, \cite{64}, with a strength predicted to be around 5 microGauss, to within 20 percent, they were indeed detected, with a strength as expected, see, e.g., \cite{1}.

Now the best measurement for the Solar neighborhood is 6 - 7 microGauss, with about 1/3 to 1/2 regular, and 2/3 to 1/2 irregular components, \cite{1}.
2.1 Critical observations

The magnetic field is a special challenge to understand in physics terms. Other critical measurements are:

The order of the magnetic field in the Galaxy is destroyed by the interstellar medium stirring on time scales of order 30 million years, as can be deduced from Cosmic Ray transport arguments. This is less than the rotation period of the Galaxy, and so any diffusive process taking many rotation periods is ruled out. In contrast, inside stars there is enough time.

Starburst galaxies such as M82 have a magnetic field, which is ordered and also in near-equipartition. And yet the starburst is just a few tens of millions of years old. The conclusion is once more that the resurrection time scale of the magnetic field is of order 30 million years.

It appears that the magnetic field has an overall orientation, with its direction along the spiral arms inwards always, [24]. This seems to be a general pattern for spiral galaxies, as long as they are not interacting. There is also a different point of view as regards our Galaxy, [15, 16, 17], but a worry is that local effects overshadow the global picture for us; and so many expect that also in our Galaxy the magnetic field is pointed globally along the spiral arms inwards. However, we have to keep in mind that the observational statistics are still small.

Galaxies which have a strong magnetic field, but also solid body rotation over that radial range of the disk where the magnetic field has been measured, are another important test.

Clusters of galaxies have a magnetic field which normally appears to be quite strong, with a lower limit of several percent of equipartition in energy density, [9, 10]. There are two examples of clusters which seem to have fields close to equipartition, e.g. [13]. Even large scale sheets in the distribution of galaxies have been successfully measured to have magnetic fields, [20]; in that case the strength is not very certain, between 10 and 100 nanoGauss range the best estimates, but the fields could also be stronger; just the existence is certain, since that argument is based on the observed synchrotron emission.

2.2 History and reviews

The history of this topic is large: The dynamo process was invented twice, by Steenbeck and his associates, in [65, 66, 67, 21, 68, 22, 69, 70, 50, 51, 52, 53, 54, 23] and by Parker, in [37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 32] and [47, 48, 49]. Recent reviews are in [33, 25, 1, 30, 27, 28]. Large scale magnetic fields are discussed in [72, 29, 56, 7, 26, 8, 6, 73].

2.3 The challenge

On the basis of the data the challenge is to find a mechanism to generate an ordered magnetic field which is fast. We outline a proposal here that may be
able to do this. First attempts along these lines were made in [5, 14]. This work reported here is another step along the way, but we are nowhere near finished.

3 The equations for mass and current

We follow the arguments of [2, 3, 11, 63, 36], in the notation of [55].

Ions have mass \( m_i \), charge \( Z \), and velocity \( v_i \) and electrons mass \( m_e \) and velocity \( v_e \). \( \mathbf{E} \) and \( \mathbf{B} \) are the electric and magnetic field. Ions have a density \( n_i \) of with an average charge of \( Z \), and electrons have a density \( n_e \). Then the two equations of motion for ions and electrons are

\[
n_i m_i \left( \frac{\partial}{\partial t} v_i + (v_i \cdot \nabla) v_i + n_i m_i \frac{\nu_i}{3} \right) \nabla \text{div} v_i + \nabla P_i - n_i m_i \nabla \Phi + P_{ie} \tag{1}
\]

and

\[
n_e m_e \left( \frac{\partial}{\partial t} v_e + (v_e \cdot \nabla) v_e + n_e m_e \frac{\nu_e}{3} \right) \nabla \text{div} v_e + \nabla P_e - n_e m_e \nabla \Phi + P_{ei} \tag{2}
\]

where \( \omega_p \) is the pattern velocity of any preferred rotating system of reference, of interest in the case we consider a spiral stationary pattern. We need to point out that these equations describe the forces and so the changes in the orbit of any ion or electron (positron), but they do not contain the steady flow of ions/electrons, which are carried around in a circle perhaps; this can happen in the neighborhood of the intense radiation field of an accretion disk around a black hole: The radiation field pushes on the skin of interstellar material close to it, and so a charged layer is formed; this charged layer is carried around in its orbit with the material, and so a current is built up. This current then produces a specific unique symmetry, as discussed below.

The stress-tensors \( \Psi_e \) and \( \Psi_i \) are replaced with viscosity terms and the pressure gradient, \( \Phi \) is the gravitational potential, \( \mathbf{F} \) the radiative flux, acting only on electrons via Thomson scattering (cross section \( \sigma_T \)), and \( P_{ei} = -P_{ie} \) is the frictional exchange of momentum between ions and electrons, while the term involving the viscosity \( \nu_i \) and \( \nu_e \) allows for accretion disks.

We assume, that we can ignore the dependence of the density in the viscosity terms, and that the viscosity is the same for electrons and ions to first order, since it clearly depends on large scale flows, and at the level at which we are initially interested in, not on the microphysics. Therefore we set \( \nu_i = \nu_e = \nu \) for
the kinematic shearflow viscosity, and also $\zeta_i = \zeta_e = \zeta$ for the specific volume viscosity. These last assumptions are made here only for initial simplicity.

We define the density $\rho$, flow velocity $v_i$, $\sigma_{i,e}$ the net charge density, and electric current $j$ in an obvious way,

$$
\rho = n_i m_i + n_e m_e \\
\rho v = n_i m_i v_i + n_e m_e v_e \\
j = e(n_i Z v_i - n_e v_e) \\
\sigma_{i,e} = n_i Z - n_e \\
n_i v_i m_i (1 + Z m_e/m_i) = \rho v + \frac{m_i}{e} j \\
n_e v_e Z (1 + Z m_e/m_i) = \rho v - \frac{m_e}{e} j
$$

Cosmic Ray particles can be part of these equations, but due to the two-stream instability they cannot flow faster than the local Alfvén speed. There is a possibility to create secondaries, electron-positron pairs from charged pion decay, arising from p-p collisions between cosmic ray particles and the interstellar medium; another way to consider this to allow for charge exchanges, recombination and ionization: Let then $S_e/n_e$ be the rate of such processes. $S_i$ and $S_e$ is the rate of density increase of ions and electrons, respectively.

The Maxwell equations are

$$
\text{div } E = 4\pi e \sigma_{i,e} \\
\text{div } B = 0 \\
\text{curl } E = -\frac{1}{c} \frac{\partial}{\partial t} B \\
\text{curl } B = \frac{4\pi}{c} j + \frac{1}{e} \frac{\partial}{\partial t} E
$$

The Maxwell equations allow to relate observed magnetic fields to the underlying symmetries, and electric currents. In the following we ignore the electric field inside a shockwave at first. We add the two main equations, to obtain the standard equation of motion, including magnetic fields and currents, and also subtract these equations to obtain the equation of motion for electric currents.

### 3.1 Mass and momentum flow

We consider the galactic disk, in the observer’s inertial frame system, i.e. keep the rotational flow $v_\phi$ with all spatial gradients. The equations allow for a wind from the disk through the term $v_z$, a Galactic wind as an analogy to the Solar wind, driven by Supernova explosions, individual massive star winds, and HII regions.

$$
\rho \frac{\partial}{\partial t} v = \frac{\sigma_T F Z}{c m_i} \frac{\rho}{1 + Z m_e/m_i} + \\
+ \rho v \Delta v + \rho (\nu/3 + \zeta) \text{grad } \text{div } v
$$
\[-2\rho \omega_P \times \mathbf{v} + \mathbf{T}_i + \sigma_{i,e} e \mathbf{E} + \frac{1}{c^2} \mathbf{j} \times \mathbf{B} - \nabla P - \rho \nabla \Phi \] (5)

plus non-linear terms

\[
\mathbf{T}_i = -\mathbf{v}_i m_i (\text{div}(n_i \mathbf{v}_i) - S_i) -
- \mathbf{v}_e m_e (\text{div}(n_e \mathbf{v}_e) - S_e) +
+ \mathbf{v} \text{div}(\rho \mathbf{v}) - \mathbf{v} (m_i S_i + m_e S_e) -
-m_i m_i (\mathbf{v}_i \cdot \nabla) \mathbf{v}_i -
-m_e n_e (\mathbf{v}_e \cdot \nabla) \mathbf{v}_e
\] (6)

Momentum exchanges \(\mathbf{P}_{ie} + \mathbf{P}_{ei} = 0\) balance out, and the total pressure sum is \(P = P_i + P_e\).

### 3.2 Electric current and momentum flow

The momentum exchange term is \(\mathbf{P}_{ei} = e n_e \eta \mathbf{j}\) with \(\eta\) the resistivity. Subtracting the two main initial equations for ions and electrons gives

\[
\mathbf{T}_e = -Z \mathbf{v}_i (\text{div}(n_i \mathbf{v}_i) - S_i) +
+ \mathbf{v}_e (\text{div}(n_e \mathbf{v}_e) - S_e) +
-Z n_i (\mathbf{v}_i \cdot \nabla) \mathbf{v}_i + n_e (\mathbf{v}_e \cdot \nabla) \mathbf{v}_e
\] (7)

\[
\frac{1}{e} \frac{\partial}{\partial t} \mathbf{j} = \mathbf{T}_e + \frac{1}{m_i} \nabla P_i - \frac{Z}{m_i} \nabla P_e -
-2 \frac{\rho \omega_P}{e} \times \mathbf{j} - \frac{\sigma T F Z}{m_e c m_i 1 + Z m_e / m_i}
- \sigma_{i,e} \nabla \Phi + \frac{1}{e} \rho (\nu / 3 + \zeta) \text{grad div} \mathbf{j} + \frac{1}{e} \rho \nu \Delta \mathbf{j} -
- \sigma_{i,e} (1 - \frac{Z m_e}{m_i}) \mathbf{E} + \frac{e Z \rho}{m_e m_i} (\mathbf{E} - \eta \mathbf{j} + \frac{\mathbf{v}}{c} \times \mathbf{B} +
+ \frac{m_i}{Z \rho c} (\frac{Z m_e}{m_i} - 1) \mathbf{j} \times \mathbf{B})
\] (8)

and with a properly modified term \(\mathbf{T}_{e,\star}\):

\[
\frac{m_e m_i}{e^2 Z \rho} \frac{\partial}{\partial t} \mathbf{j} = \frac{m_e m_i}{e Z \rho} \mathbf{T}_{e,\star} + \frac{S_e m_e m_i}{n_e e^2 Z \rho} +
+ \frac{m_i}{e Z \rho} \left( \nabla P_e - \frac{Z m_e}{m_i} \nabla P_i \right) -
- \frac{\sigma T F}{e c} \frac{1}{1 + Z m_e / m_i} +
+ \frac{m_e m_i}{e^2 Z} (\nu / 3 + \zeta) \text{grad div} \mathbf{j} + \frac{m_e m_i}{e^2 Z} \nu \Delta \mathbf{j} -
\]
\[-\frac{m_i}{Z \rho} \sigma_{i,e} (1 - \frac{Z_{m_e}}{m_i}) \mathbf{E} - \eta \mathbf{j} + \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} +
\]
\[-\frac{m_e m_i}{e Z \rho} \sigma_{i,e} \nabla \Phi + \frac{m_i}{Z \rho_{pec}} (\frac{Z_{m_e}}{m_i} - 1) \mathbf{j} \times \mathbf{B} \]  

(9)

In deriving these equations we have made various simplifying assumptions in order to keep them tractable, as we will discuss below; we have not insisted to keep all terms involving the lack of charge neutrality.

3.3 Number estimates

From the saturation argument of [36] as applied to Galaxy, and its interstellar medium (hot phase, detected by ROSAT, see [62], ASCA observations [18], RXTE measurements, [71]) we obtain estimates for the various currents and scales.

- The curl-operator scale is \(10^{23.2}\) cm, from \(2\pi r\), where \(r\) is the radial distance from us to the center of the Galaxy, about 8 kpc. This we use to infer from Maxwell’s equation the average electric current in the Galaxy, mentioned below.

- The \(\nabla\)-operator, here has a scale of 2 kpc = \(10^{21.8}\) cm, from the scale of the hot gas, and the scaleheight of the magneto-ionic disk is 1.8 kpc [61], basically the same.

- The resistivity according to Spitzer, [63], is of order \(10^{-17}\) sec, but highly uncertain; the uncertainty is many powers of ten. This resistivity corresponds to the limit that binary collisions dominate the exchange of momentum, but if the Larmor frequency were to dominate, then the resistivity could be very much higher, possibly by more than ten orders of magnitude.

- The hot gas has density is \(3 \times 10^{-3}\) cm\(^{-3}\), and its temperature is \(4 \times 10^{6}\) K [62], with a total gas pressure of \(10^{-11.4}\) dyn/cm\(^2\).

- The total magnetic field is approximately \(10^{-5.2}\) Gauss, and so the total magnetic field pressure is \(10^{-11.8}\) dyn/cm\(^2\); we have therefore approximately \(P_{CR} = P_B\), \(P_{CR} + P_B = 10^{-11.8}\) dyn/cm\(^2\).

- The electric current is \(j = 10^{-18.9}\) cgs units. For the observed symmetry of the magnetic field there must be a current. The existence of this current is the key to our approach.

- These numbers are uncertain, probably to within somewhat less than a factor of 2 (see E. Berkhuijsen in Beck et al. [1]). A much higher uncertainty derives from the assumption, that everything is basically smooth.

We make the implicit assumption here, that all relevant time scales are of order \(3 \times 10^7\) years, or longer; we also assume that the topology of the medium, permeated by magnetic fields, hot and cold gas, and cosmic rays is basically
smooth, with no critical different topologies, such as shocks. We basically assume at this stage, that shocks exist, but do not drive any relevant part of the system.

3.4 Symmetries

In the following we will use the symmetry with respect to the symmetry plane \( z = 0 \) as a first guiding principle:

We introduce the following language:

- We will call a quantity, vector component or scalar “even(\( z, z^n \))” in the case, that the quantity can be expanded into a power series in \( z \), that contains only even terms, and starts with \( z^n \), where \( n \) is an even number. We will use the expression even(z, 1) in the case that the quantity is a constant in its first term, so \( n = 0 \).

- We will call a quantity, vector component or scalar “odd(\( z, z^n \))” in the case, that the quantity can be expanded into a power series in \( z \), that contains only odd terms, and starts with \( z^n \), where \( n \) is an odd number.

- We will have to check whether any argument forces us to use a mixed expression - but we have not found one yet.

- We will use the language (even, even, odd), when the three vector components in cylindrical coordinates \( r, \phi, z \) are in that sequence even, even, and odd, or, e.g., (odd, odd, even) in a different case.

Looking at Maxwell’s equations and the data, we find then that the main symmetries of different quantities are as follows:

- \( \mathbf{B} \) is (even, even, odd).

- \( \mathbf{j} \) is (odd, odd, even).

- In the observer frame \( \mathbf{E} \) is also (odd, odd, even), as \( \mathbf{j} \). \( \mathbf{E} \) derives from a Lorentz transformation of a shock frame \( \mathbf{B} \)-field, and so is not an independent source term.

- The expression \( \mathbf{v} \times \mathbf{B} \) is (odd, odd, even).

- The expression \( \mathbf{j} \times \mathbf{B} \) is (even, even, odd).

- The expression \( \nabla P \) is (even, even, odd).

There is an alternate pattern, in which the magnetic field shows (odd, odd, even), and the electric current shows (even, even, odd) symmetry. It cannot be excluded, that some galaxies have this symmetry. In the following we will pursue the discussion of the main symmetry.

What we find then in the case of the equations for mass flow and electric current flow is that the following is true:
• In the equation for mass flow we have only terms that are either independent of \( \mathbf{j} \), or \( \mathbf{B} \), or quadratic. All these terms have the symmetry (even, even, odd). There are some linear cross-terms, which should cancel each other out; they cannot act as source terms due to a failure to match symmetries.

• In the equation for the electric current the entire equation splits up into terms, that are either (odd, odd, even), or (even, even, odd). Those terms which are linear in either \( \mathbf{j} \), \( \mathbf{E} \) or \( \mathbf{B} \) are all (odd, odd, even). Those terms which are either a source term, or quadratic, are all (even, even, odd).

• Interestingly, the terms involving the pressure gradient, and also the Hall term, which are of similar numerical magnitude, do have the same symmetry as well. They do “belong together”.

The first conclusion is then, with the equations for mass flow, and the electric current as written here, the equations are independent of the \((+,-)\) symmetry with respect to the sign of \( \mathbf{B} \) and \( \mathbf{j} \). Replacing both \( \mathbf{B} \) and also \( \mathbf{j} \) with the same numbers, but with all signs changed to the opposite, does not change the equation. We conclude, that the physics which determines the sign is not yet adequately described by these equations.

### 3.5 Battery effect and dynamo action

Now two arguments can be made:

#### 3.5.1 The dynamo process

Considering the overall equation for driving a current, and taking the curl, and dropping all irrelevant terms, one obtains the basic equation for a discussion of the dynamo process, allowing for Coriolis forces and turbulence in a rotating system. The large number of original references were already given in the introduction.

#### 3.5.2 Battery effect

Assuming no magnetic field to exist a priori, one obtains the Battery effect, \([2, 3]\). Again taking the curl of the entire equation for the electric current, we have one important term

\[
\text{curl} \left( \frac{m_i}{eZ\rho} \nabla P_e \right) \sim \nabla \left( \frac{m_i}{eZ\rho} \right) \times \nabla P_e
\]

(10)

In an accretion disk, where density and temperature are usually governed by very different microphysics, this term is certainly non-zero, and drives an electric current. This the original effect pointed out by the early authors \([2, 3]\). This is a slow process, although in its limit it gives the reasonable estimates for magnetic fields, see \([11]\). The key argument here is that an electric current...
drives the generation of the magnetic field; this electric current is driven by the rotation of the system.

3.6 Scaling the hierarchy

Using the observations, and Maxwell’s equations we can discern the numerical relevance of all the terms in the two main equations, for mass flow and for the electric current; the numbers have been given above already. In this we assume at first that there are no discontinuities, to obtain a first guide line of what the observations are telling us.

Three levels of numerical strength exist in the system:

The level structure exists already in the equations connecting momentum flow and electric current to electron and ion velocities. There are two terms also at a lower level: the momentum flow of the electric current is lower than the real mass momentum flow by $10^{-14.1}$ and $10^{-17.7}$, respectively. As a consequence this structuring also exists in the fuller equation above, the equation describing the driving of the electric current.

- $E$ and $\frac{1}{c} \times B$ of order $10^{-8}$ cgs units, using our Galaxy as the prime example.
- Pressure gradients and the Hall term are about $10^{-15}$ to $10^{-18}$ times smaller. The radiation driving term is about a factor of 100 weaker again.
- In $T_e$ the $(\mathbf{j} \cdot \nabla)\mathbf{v}$-terms, the time dependent term, the ionization term (assuming an ionization time scale of $3 \times 10^7$ years as for the time dependence), the viscosity terms are all again about $10^{-15}$ to $10^{-18}$ times smaller. The resistivity term is nominally a factor of about $10^4$ larger, but very badly understood.

We introduce here a way to “scale the hierarchy”, by noting that there may be a large scale shock wave pattern in the Galaxy:

In a spiral galaxy there is a spiral pattern of young massive star formation, and an associated spiral pattern of supernova explosions of just those stars. These supernova explosions produce nearly spherical shockwaves, that propagate outwards, and can reach quite large distances in the tenuous medium. It is easy to show that these shockwaves can overlap in a way that there is always a coherent large scale connected net of shock wave surfaces, locally highly time-dependent, but globally stationary. Locally these shock waves are very time-dependent, and quite fast, obviously faster than the speed of sound in the hot medium, but the global pattern is slow, with a speed much less than the speed of sound in the hot medium. So a comparison with the waves on a beach may be appropriate, very strong waves, as in the Bretagne on the north-western shore of France, but limited by the beach itself and the tides, running up the beach as breakers with a speed that children match only with difficulty.

Let us check on the time scales: In a galaxy like ours we have about one supernova every 100 years, and maybe 1 supernova every $10^3$ years in the appropriate mass range, those corresponding to zero age main sequence mass above
about 15 to 20 solar masses. This means that a supernova expands into the tenuous hot interstellar medium to a radius of about 50 pc within $2.5 \times 10^4$ years, and the shock then still has a velocity of 500 km/s, a small multiple of the speed of sound in the hot medium. Taking then the notion, that the younger supernovae occur all along the line of the spiral arms, we have about $10^{-6}$ yr$^{-1}$ and pc$^{-1}$. If each supernova reaches out to 100, pc, within $2.5 \times 10^4$ years, then we have at this frequency about 2 supernovae occurring per 100 pc and per this time, so just a sufficient number.

We need to inquire about the “front” and the “back” of this geometrical set of exploding stars: There is a minimum age for stars to explode as supernovae, but there is a long tail of larger ages, and so one can expect that there is a front pattern, but no back-pattern. At the backside of the spiral pattern there is no corresponding shock; everything peters out.

This concept is similar to the concept for the young supernova shock itself, as in [4].

In such a shock an electric field exists, driven by the fact that ions and electrons have a different mass. Then the overall global spiral shock drives a current system, a sheet current, and the current is very strong inside the sheet, but weak elsewhere. We note that a sheet current produces a homogeneous magnetic field, with a different sign on opposing sides. The current may be driven by the $\mathbf{E} \times \mathbf{B}$ drift inside the shock sheet; also, the gradient in pressure and/or temperature in this shock can drive a current. Once one sign is established, it may prevail due to the overall structure winning by emphasizing the common vector components, i.e. those geometrically aligned with the overall shock structure. Since an $\mathbf{E} \times \mathbf{B}$ drift pushes positive and negative charges in the same direction, only inertia can produce a real electric current; inertia is only important if the velocities reach close to thermal velocities (or relativistic, unlikely here). The requirement to transport angular momentum transport implies that the sign permeates everything in the same way, since any region, where the sign changes would violate the strict direction of angular momentum transport.

Does this solve the problem?

It goes part of the way towards solving the problem by making all three levels equivalent, since the second level was small just by the ratio of the Larmor radius of thermal hot ions to the overall scale, and a shock wave pushes the strength of these terms up by exactly this factor. With a strong sheet-like electric current, stronger by about $10^{14}$, but geometrically limited to the shock sheet, we have then equivalence between the first and the second level. And again the third level was smaller than the second by again the same factor. The third level involves a spatial derivative and the current, and so is doubly pushed up in level. Therefore, only in the shock sheet and its immediate environment do we have equivalence of all three levels, previously disjunct. With a shock wave all three levels are becoming equivalent in numerical strength; however, the shock does not change the symmetries.
3.6.1 The current sheet

This means that we have to consider whether such a current can actually be carried by the sheet: the thickness of the sheet is about a postshock thermal Larmor radius $r_g$, and so about $10^9$ cm, stronger than an average current by the ratio of length scales, $\pi r$ vs. $r_g$. So the electric current in the sheet is about $10^{-5}$ cgs units. This means that the drift velocity is required to be about thermal, so all ions and electrons participate, with a velocity difference about equal to the thermal velocity. This thermal velocity here is the preshock velocity, so the drift can be slow compared to the postshock velocity; however, in order to get a current, we require that electron and ion velocities are quite different. We emphasize again, that this very strong electric current is only in the shock-sheet, and in order to provide the magnetic field observed, has to go vertically.

3.6.2 Angular momentum transport

In this model of expanding supernova remnants angular momentum is mixed, and exchanged, which means that it is effectively transported. The transport is with the azimuthal velocity difference across a supernova remnant, and with the diameter of the supernova remnant. And as shown by Lynden-Bell & Pringle, [35], and by Duschl et al., [12], this leads to an angular momentum transport that scales with some fraction of the radius $r$, and the azimuthal velocity $v_\phi$, with a factor of order 0.01. This picture developed here does just that. So this way of using large scale shock waves, locally highly non-stationary but globally stationary shock waves, does transport angular momentum. Whether this is already at the level implied by the observations is not clear; the numbers suggest that this mechanism is not sufficient. We need an additional enhancement.

3.7 What determines the sign?

Now we have found that even with all the details we do not get a sign prevailing in the detailed description of the flow; this is exactly the same conclusion that Krause & Beck came to in their original work on the sign of magnetic fields in disk galaxies.

3.7.1 The role of the central black hole

Here we wish to explore one way to obtain a specific sign: In the case that a powerfully radiating accretion disk surrounds a central massive black hole, then we have a strongly ionizing ultraviolet photon field. This photon field will ionize and actually charge up a skin in the surrounding matter. Carrying this skin of net charge around produces a circular electric current, with the flow direction exactly the same as the rotation of the material, presumably with the same sense of rotation as the central black hole. This will then produce in turn a magnetic field with a specific sign, aligned with the rotation axis of the black hole.
hole, and pointing in the direction of the spin vector. Related questions have been explored in full relativistic treatment by [19].

This then may determine a definitive sign overall, because it should infect the surrounding matter: a wave of a specific sign will then propagate outwards from this environment. At this point we do not specify how the sign of this inner magnetic field can be turned into a sign of the electric current further out. But once a specific sign is established, it will sustain itself, within the frame work of the mechanism outlined above.

From this picture there are some predictions and speculations: a) Galaxies without a central black hole will not show a specific sign in their magnetic field configuration. b) Galaxies which did not have an accretion event in a very long time, may lose their memory of the original sign. Memory may also be lost, at least for a while, in a merger event with another galaxy, especially if the merger leads to a spin-flip of the central black hole. c) In galaxies at high redshift we may be able to observe the propagation of the wave of a specific sign.

However, this mechanism does not really prefer the observed symmetry over another one, in which the azimuthal magnetic field changes sign in midplane, so a symmetry of the magnetic field which is (odd, odd, even). This latter symmetry is the one that is implicit in any symmetry coming from the central black hole and a charge distribution carried around in corotation. The effect of the radiation of the black hole prefers the alternate symmetry introduced above.

3.7.2 Transport processes?

So we have to look at another option, really a program of investigation:

Considering how the basic equation was derived from the Boltzmann equation, we realize that the stress tensor, the heat flux tensor, and the transport of angular momentum all are dumped into some convenient functions, and simple dependencies that hide the micro-physics. It appears clear from the derivation (see, e.g. Spitzer's book on plasma physics, [63]) that we require a vector, and the angular momentum flux, that is probably non-linear in $j$ and/or $B$, and has the symmetry (even, even, odd) in the expression for the mass flux, while a corresponding vector is required, which has the symmetry (odd, odd, even) in the equation for the electric current. From the idea, that this is Nature's message, it is clear that the resistivity has to approach the limit of using the gyrofrequency instead of the collision frequency, and that a non-linear behaviour is required, that leads from both the main symmetry and the alternate symmetry only to the main symmetry. Just geometrically, the vector expression $B \times \text{curl} j$ would do just that; this expression leads both the main symmetry and the alternate symmetry into driving an electric current with the main symmetry - but the relevance for Nature is at this stage mere speculation. A physical picture for this microphysics has to be left to a later discussion. What may appear at the end, is that the requirement that angular momentum flow is outwards drives the sign of the symmetries, and that we have a highly non-linear expression, using shock structures in a disk to scale the hierarchies. Shocks may appear if
the state of the gas is too extreme in its failure to transport angular momentum, and magnetic fields may correspondingly appear. It can be expected that the expressions and coefficients are not independent, just as in the theory of the thermodynamics of irreversible processes.

### 3.8 Where magnetic fields may come from

Therefore we arrive at following speculative picture of the origin of magnetic fields: Stars inject a fairly strong magnetic field, which is highly chaotic. This field is injected with extreme chaos, but from the ram pressure condition for the winds with an Alfvénic Machnumber of order 3, \([57]\), and so probably with only a factor of order 10 below equipartition. It is actually open to question, whether more is actually required in an inhomogeneous picture of the interstellar medium. The sheet current in the global shock pattern keeps restablishing the strength and the symmetries of the overall regular field, while all the stellar activity produces all the small scale perturbances.

The sheet current involves a very large scale shock, locally unsteady, but globally steady. This is reminiscent of the early discussions in spiral shock waves, \([34, 58, 59, 60]\). We are reinventing a large scale shock, highly unsteady locally, with a very high maximum local shock velocity, but a rather small pattern velocity.

The global shock proposed here is intimately connected to spiral structure, and thus to the overall flow of angular momentum outwards in any accretion disk. One might speculate whether such a spiral shock could also occur in accretion disks without star formation, and whether in that case it could again drive a sheet current, and thus provide a power source for overall magnetic fields. Could it be that magnetic field generation is connected to the accretion phenomenon for ionized disk as soon as they show a spiral shock structure?

One may ask whether such a shock pattern should not be visible? And indeed this is an interesting question worthwhile to pursue with X-ray spectroscopy and high spatial resolution data. X-rays may provide a crucial test for this speculative proposal.

### 4 Conclusions - Future

Magnetic fields are present in the universe, usually strong and relevant.

Where they come from is uncertain, and an attempt outlined here is still incomplete, but we hope, we will be able to figure out using just stars, and the physics of the ionized interstellar medium, how magnetic fields may be generated.

We have outlined a program of investigating the Boltzmann equation to resolve the connections between heat flow, angular momentum transport, and driving currents in an accretion disk. Such an investigation may finally yield the sign of the prevailing magnetic field, and if so, also elucidate the physics of angular momentum transport and magnetic field generation in disks at the
same time.

What we have proposed here is to suggest that the overlapping shockwaves from supernova remnants produce a locally unsteady, but globally steady shock structure, which is rather similar in its pattern with the early attempts to find a global spiral shock; however, through its local unsteadiness it is really quite different in its physical properties. This global shock structure drives a sheet current through its electric field and strong gradients in pressure and temperature, which in turn produces by its overall symmetry a global magnetic field, and so rejuvenates continuously the overall topology of the Galactic magnetic field.

Cosmic magnetic fields are key to the transport of charged particles throughout the Universe, at any energy.

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