ORIGIN OF COSMIC MAGNETIC FIELDS

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Lecture based on a weekend of discussion with P.P. Kronberg at Bloomington, Indiana

History and Observations

- Cosmic magnetic fields were predicted to exist in our Galaxy
- a) based on the optical polarization of stellar light, and
- b) on the isotropy and energy density of cosmic rays
- Prediction was 5 μGauß with an uncertainty of 20 % (L. Biermann)
- Best value today is 6 - 7 μGauß (E. Berkhuijsen), adding irregular and regular magnetic fields

Observations

- Magnetic fields obviously exist on the Sun, and in most stars, both low mass and very high mass
- Magnetic fields exist, and probably play a decisive role in Gamma Ray Bursts, and in
- Relativistic jets from very near black holes, ubiquitously present in the centers of almost all galaxies, including our own
- Magnetic fields were then detected in other galaxies, in clusters of galaxies, and also in the large scale structure

Ansatz

- Battery mechanism (L. Biermann 1950): In a rotating system surfaces of constant pressure and constant density do not coincide, and so an electric current is driven
- Cannot be compensated by charge redistribution
- Provides seed field - very weak
- Almost all stars rotate, low mass stars rotate fast early in their life, high mass stars probably rotate fast all their life
- Most stars have of order 10^{10} rotation periods in their life time
- Both low mass and high mass stars have winds, that eject magnetic fields

Massive stars

- Powerful winds of high mass stars get help from the magnetic field in their driving:
- The interaction between photons and the gas in the wind is through a wave excitation, and the wave speed is the "coupling constant" (St. Owocki, H. Seemann): Alfvén waves much faster than sound waves
- Supernova explosions also eject magnetic fields
- In the interstellar medium of the Galaxy then highly tangled source fields, but near 10 % of equipartition possible
- Average fields must be very weak, and have little directional correlation over large scales

Dynamo mechanism

- How to strengthen a magnetic field?
- Dynamo mechanism, bubble up, twist, fold over (M. Steenbeck, F. Krause, E. Parker): key elements convective motions and rotation
- Requires many rotation periods
- The required times exist for stars
- Is there sufficient time for galaxies?
- Fastest version of such a theory (H. Lesch et al.): Cosmic ray driven dynamo
- Local time scale Alfvénic time vertically across thick disk
- Not shown yet: How to provide large scale coherence

Distribution

- Regular components of magnetic fields in galaxies coherent over very large scales, and often seem to point inwards along a spiral pattern (F. Krause, R. Beck); or in a circle
- Ejection from galaxies through winds (also work by P.P. Kronberg et al.), strong in galaxies with starbursts and lots of star formation - common in their early life (redshift at and beyond 1 - 2)
- Ejection from Active Galactic Nuclei by jets, can reach Mpc scales
- Then carried along in Large Scale Structure flow (work with H. Kang, H. Lee, D. Ryu)
- So, galaxies and their magnetic fields are the missing link in this - stars, ejection from stars, ejection from galaxies

Key difficulty

- ISM in our Galaxy, and Starburst galaxies such as M82
- Time scale of both: $3\,10^7$ years
- for heating, cooling, magnetic field regeneration - note, that ISM highly inhomogeneous
- On this time scale **disorder is injected** into magnetic field pattern
- This time scale required for reordering magnetic field, or for **injecting ordered** field continuously
- Nature manages to keep coherent order over length scales far larger then the thickness of the hot disk (4 kpc in our Galaxy) despite the chaotic forces

Sharpening of the problem

- Sofar the argument was: How to strengthen a weak magnetic field, keeping some order as you go along
- In this line of reasoning the seed field could come from any source, could be primordial, from magnetic monopoles, or an early version of the Battery mechanism connected to the structure formation
- However, now we need to recognize: The strength of magnetic field may not be the difficulty, but the large scale order
- It is obviously easy to inject fairly strong magnetic fields in the interstellar and/or intergalactic gas

Further sharpening of the problem

- However, the sources are random, and the forces of chaos (star formation, stellar winds, supernova explosions, ..) randomize the field additionally
- Clusters of galaxies do have complete chaos in the magnetic field, and this is just due to infalling fresh gas, differential motions of the gas, to the random injection from galactic winds and radio galaxies - so this is what we would naively expect the ISM to look like
- **How do we keep even a semblance of any ordered magnetic field in the disk of a galaxy? And do this on 30 million years?**

Injecting order

- Inverse cascading: Contamination of a specific sign and direction from one region to the next - diffusive and so too slow probably
- Shear in disk - the first idea - (recent work by K. Otmianowska-Mazur et al.) can produce order on one rotational time scale - probably still too slow
- Shear flow in outflows - (recent work by M. Urbanik et al.): Some galaxies show evidence for regular outflow, and X-shaped pattern in radio polarization in edge-on galaxies - not clear how this translates into a regular pattern in the disk
- Vertical plumes in the outflow: A very local phenomenon in the disk - would need some folding down, and then a side ways active inverse cascade to avoid a layer cake pattern

Electric sheet currents ?

- Are there electric sheet currents in large scale shocks? Geometry: vertical sheet (like a curtain, or aurora borealis), perpendicular to the flow direction and local magnetic field
- Very large scale shock, locally unsteady, but globally steady.
- The bead pattern of numerous supernova explosions along the front of a spiral arm.
- Reminiscent of early work by C.C. Lin, F.H. Shu et al..
- A large scale shock, highly unsteady locally, with **very high maximum local shock velocity, but rather small pattern velocity**.

Electric sheet currents ? ?

- Electric currents due to drifts in large scale shock.
- The global shock proposed here intimately connected to spiral structure, and thus to overall flow of angular momentum outwards in any accretion disk.
- In the expansion of supernova remnants, angular momentum conservations entails lots of local shear, and local rotation; the information of the angular momentum direction is present and plausibly influences the direction of the electric current system, and therefore the direction of the magnetic field.

Electric sheet currents ? ? ?

- Equation of motion for electric current system: Hierarchy for smooth distribution of fields: standard equations
- In case of large scale shock waves hierarchy scaled, so that equation of motion for electric currents much more general:
- Terms usually ignored increase in strength by the factor of the ratio of large scale over Larmor radius of thermal protons (about 10^{15}
- Symmetries can be used to describe the various terms: such as (odd, odd, even) relative to a series expansion in z, in a cylindrical coordinate system (r, ϕ, z), see astro-ph/0302168

Conclusions

Magnetic fields are present in the universe, usually strong.

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.

The role of primordial magnetic fields is highly uncertain, but present observations do not require primordial magnetic fields.

Cosmic magnetic fields are key to the acceleration and transport of charged particles throughout the Universe.

Key question: How to obtain order in chaos in the magnetic fields in the Galaxy.

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