Transport in Magnetic Fields

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Diffusion of Charged Particles in Magnetic Fields

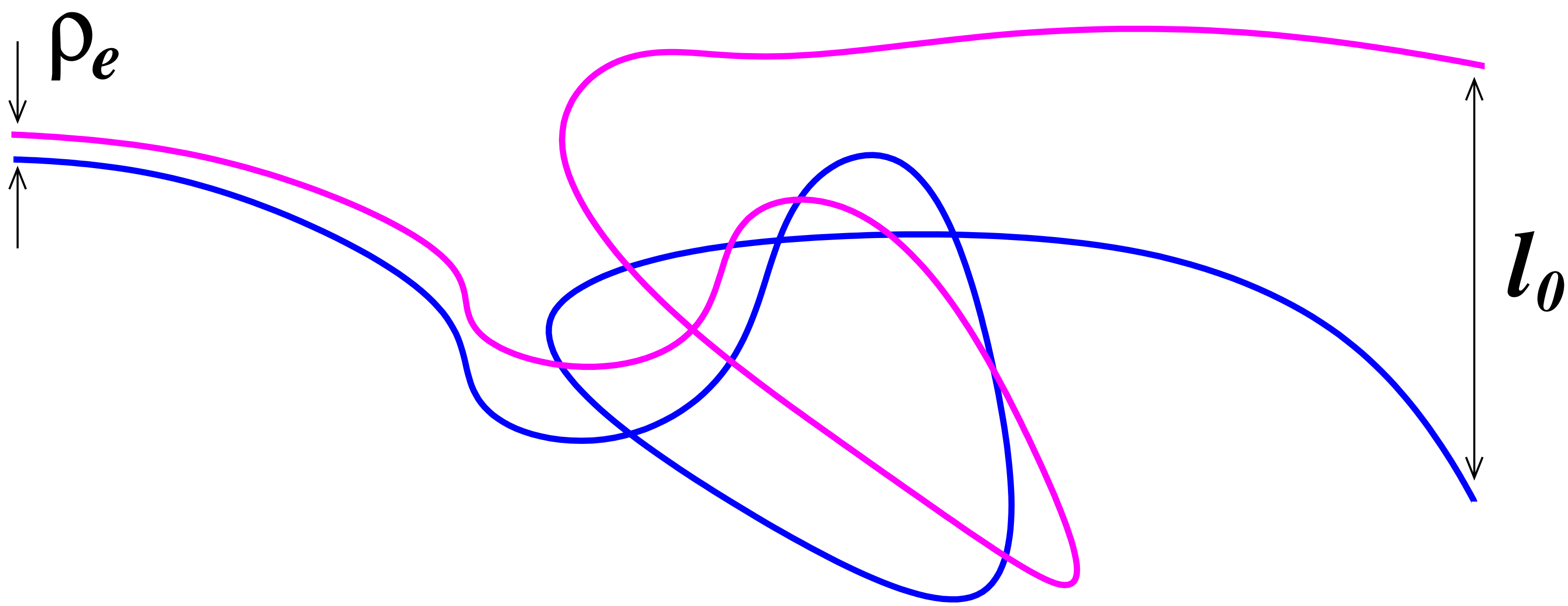
The Major Goal: Build a good quantitative theoretical model of particle transport in magnetic fields. This model can be analytical or can be based on numerical simulations or can be a combination of both.

Motivation:

- Confinement of cosmic rays in galaxies: cosmic rays are produced by supernovas and models of their transport are still crude.
- Confinement of charged particles in laboratory experiments.
- Diffusion of charged particles is closely related to thermal conduction in magnetic fields (next slides).
- Can also be related to transport of angular momentum in disks.

Single-scale field models (Rechester & Rosenbluth, Chandran & Cowley):

$$\frac{d\Delta}{dl} \sim \frac{\Delta}{l_0} \;\Rightarrow\; L_{RR} \sim l_0 \ln \frac{l_0}{\rho_e} \;\Rightarrow\; D \sim \frac{(L_{RR}/l_0) l_0^2}{L_{RR}^2/D_{\|}} \sim \frac{D_0}{3\ln(l_0/\rho_e)}$$



Multi-scale field heuristic models (Skilling *et al*):

$$\frac{d\Delta}{dl} \sim \frac{\Delta}{\Delta} \;\Rightarrow\; L_{RR} \sim l_0 \;\Rightarrow\; D \sim D_0/3$$

A quantitative model with $\delta B << B_0$ (Jokipii).

Proposed Tasks:

- Simulations:
  - Study transport of passive particles in synthetic magnetic fields with prescribed spatial spectrum, stationary fields and fields with prescribed decorrelation in time $\Rightarrow$ role of collisions, field spectrum and its anisotropy. nearest
  - Check present single-scale and multi-scale field models by using simulations. nearest
  - The same but use magnetic fields provided by turbulence/dynamo problems in existing codes. nearest
  - Include back reaction of charged particles: tracking of passive particles is available in Flash, back reaction may be included.
  - Study the second-order Fermi acceleration by magnetic fluctuations.
  - Simulate/make theory for transport in MST and other plasma devices by using the measured fields as the input.

- Theory:
  - Compare Jokipii results to the results by others (Skilling, Medvedev, Chandran). Understand the role of three effects: (1) wondering of fields lines in space; (2) their evolution in time; (2) exponential divergence of particles from a field line because of drifts, collisions and local field shear, $b_{\alpha,\beta} \approx$ const. Do we need to combine all these effects together and will we get different diffusion regimes (as function of drift rates and collision rates)? *Proposed by Stas Boldyrev.* nearest
  - Note by Jokipii: In galaxy/protogalaxy magnetic spectrum does not extend all the way down to gyro-radius. As a result, Skilling/Medvedev multi-scale theory can be invalid. nearest
  - Compare theoretical models (old and/or new) with transport in experiments.
  - Extend Jokipii model to finite field fluctuations, $\delta B \sim B$. This is hard to do. Probably could use results of numerical simulations as the starting point.

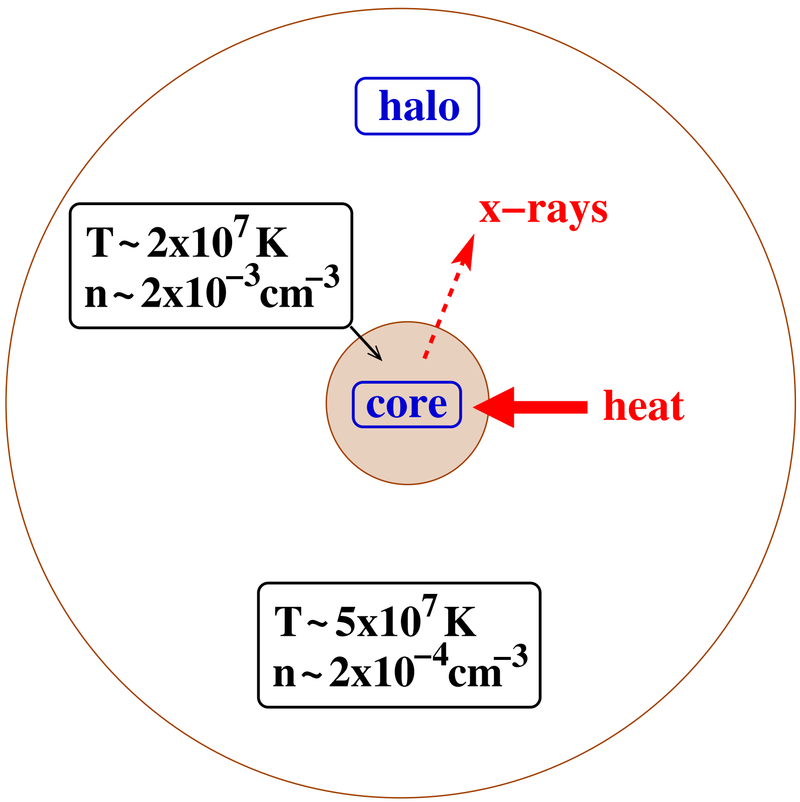
- Experiments:
  - Continue/improve MST measurements that are so far not totally conclusive and do not seem to confirm Rechester-Rosenbluth heuristic theoretical estimates. Use proton/ion injection in experiments to compare transport of charged particles with simulations of transport of low energy cosmic rays. nearest
  - Studies of energy cascade and small-scale density fluctuations in the LArge Plasma Device (LAPD). *Proposed by Robert Rosner and Univ of Chicago Group.* Would it be also possible to study transport of charged particles and particle-wave interactions in the LAPD?

Thermal Conduction in Magnetic Fields

The Major Goal: Develop a complete model of thermal conduction in magnetic fields.

Motivation:

- Cooling flows and formation of clusters of galaxies.



- Spitzer thermal conduction time in galaxy clusters is $t_{\rm S} \sim 3 \times 10^8\,{\rm yrs} \ \ll\ t_{\rm H} \sim 10^{10}\,{\rm yrs}$.
- Magnetic fields in clusters of galaxies $\Rightarrow$ lower thermal conduction.
- Cooling flows (exist only if heat conduction is low).
- Formation of clusters of galaxies and cooling catastrophe (heat conduction is too small $\Rightarrow$ a steep rise in the density of the relaxed cluster core).

$$\frac{Q_{\rm halo}}{t_{\rm cond}} \sim L_{\rm X}$$

$$t_{\rm cond} \gtrsim t_{\rm H} \Rightarrow \frac{\kappa_{\rm eff}}{\kappa_{\rm S}} \lesssim \frac{1}{30}$$

- Thermal conduction in laboratory experiments.
- Closely related to diffusion of charged particles in magnetic fields. Important fundamental question: Are they the same?

Proposed Tasks:

- Simulations:
  - Use simulations of particle transport in random magnetic fields (stationary/non-stationary, synthetic/from MHD simulations) as the starting point. Add energy exchange between passive particles by Monte-Carlo methods (with total energy conserved)? nearest
  - Include effects of thermal conduction into MHD turbulence self-consistently. Two ways to calculate heat conduction updated in time: (a) by theoretical formula using magnetic spectrum; (b) by keeping track of test particles. *Proposed by Ellen Zweibel.*
  - Collaborate with outsiders on formation of galaxy clusters.
  - Include energy exchange via collisions of passive heat conducting particles.
  - Gyro-kinetic self-consistent simulations of particles and magnetic fields. Hard to do.

- Theory:
  - Theories assume that reduction of thermal conductivity is equal to the reduction of particle diffusivity. Is reduction of thermal conductivity qualitatively or/and quantitatively different from reduction of particle diffusivity? How much different? Does the difference depend on the problem under consideration? Look at the collisional case when mfp $< l_0 << L_{\rm RR}$ and the role of collisions.
  - Review the effect of magnetic mirrors. As noted by Vladimir Mirnov, particles passing magnetic mirrors give a non-zero boundary condition for the trapped particles. This may be crucial for the escape time from a mirror. Use distribution of magnetic mirror strength measured for MHD turbulence. nearest
  - Check theoretical models (old and new more advanced) and simulation results with transport in experiments.
  - Kinetic theory for description of thermal conduction.

- Experiment:
  - Measure magnetic field fluctuations induced heat flux, which is the main heat loss mechanism. Collisional thermal conduction is much smaller. Compare results with more advanced models than Rechester-Rosenbluth; not known if the same fluctuation-driven transport that is observed in laboratory, is relevant to ISM.
  - Look at the recent astro observations. They are not conclusive, but there are some interesting questions (like observed sharp boundaries of large temperature change).