Reading Assignment for
The Physics of Galaxy Clusters (Summer Term 2020)

Lecturer: Christoph Pfrommer

in preparation of lecture 10

Next online meeting June 23, 2020, 12:00

Please read and work through the script, covering the following topics:

3.2.5 Heat Conduction

3.2.6 Thermal Instability

I prepared the following questions that should help you to understand the topics. Please read a topic first, think about it and then work through my set of questions on this topic. Some questions are going beyond what you have read in the lecture notes (indicated by *Bonus* questions). I do not expect you to answer these questions as well, but I would like you to start thinking about them and they will certainly be the starting point for our next zoom meeting. Ideally you can come up with many more questions yourself. **If you have problems with a derivation or if something is unclear, please email me those points well before the lectures**!

- **Heat conduction**
  - Derive the expression for the conduction coefficient (Eqn. 3.218) from the entropy equation with conduction as a source term (Eqn. 3.210).
  - Why is heat transported by electrons? *Bonus:* What is the role of thermal protons in a plasma and how is this effectively accounted for in hydrodynamics?
  - **Coulomb Logarithm.** Explain the "Born approximation". Calculate the deflection angle of an electron scattering in the Coulomb field of an ion. What is the physical meaning of the characteristic impact parameter?
  - Calculate the mean square of the deflection angle to estimate the cumulative, random-walk effects of many small-angle electron scatterings off ions. Argue why our choices for b_{min} and b_{max} are physical.
  - Compare the mean deflection time scale for large and small-angle scatterings. The latter is defined where the net deflection is of order a radian. Which of the two dominates in clusters?
  - Combine your results to arrive at a final expression for the conduction coefficient. Explain the origin of the strong temperature dependence ($\kappa \propto T^{5/2}$) so that the conduction term in the energy equation $\propto T^{7/2}$.
  - What is the critical physics assumption behind this derivation of conduction?
- **Thermal instability**
  - Derive the expression for the Fields length, λ_{F}, heuristically.
  - Why is it a function of entropy only? Is this also true in low-mass clusters?
  - Visualize the Fields criterion in the entropy-radius plane by adopting $\lambda_{\mathrm{F}}(K) = r$. Use this result to motivate the existence of cool core and non-cool core clusters.

- Follow the arguments and explain the main ideas of our visual stability analysis and consider radiative cooling (bremsstrahlung and free-free line emission) and heating by conduction, turbulent dissipation, and Coulomb and hadronic interactions of cosmic rays with the thermal gas.
- By introducing magnetic fields, the condition for conductive instability (Schwarzschild criterion) is substantially changed. Explain the physics of the magneto-thermal instability and the heat-flux driven buoyancy instability. What property of clusters is necessary to trigger these instabilities?
- Do you have the heat-flux driven buoyancy instability in a non-cool core cluster? Do you always have the magneto-thermal instability in clusters? To this end, recap again our calculation of filling gas into an NFW potential.