Reading Assignment for
The Physics of Galaxy Clusters (Winter Term 2021/22)

Lecturer: Christoph Pfrommer

in preparation of lecture 13

Next lecture Feb 3, 2021, 16:15

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

4.1 Optical: Galaxy Interactions and Virial Theorem

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**!

- **Observational Facts.**
  - Explain why the morphology-density relation is not in contradiction to the Butcher-Oemler effect.
  - What are the physical processes responsible for transforming star forming spirals to passive elliptical galaxies?
  - *Bonus:* what would be needed to re-ignite a passive elliptical? Where in a galaxy cluster is this happening and why is this condition not fulfilled for typical cluster ellipticals?
- **Tidal Interactions of Galaxies.** Consider the interaction of two systems discussed in the notes. A perturber galaxy P modifies the orbit of a star q in the galaxy S as a result of the gravitational interaction.
  - Let $t_{\rm tide}$ be the time for the tide to rise and $t_{\rm enc}$ be the time of the encounter of two systems S and P, then explain what happens to the internal energies of (and thus stellar orbits within) these two systems for the two limiting cases $t_{\rm enc} \gg t_{\rm tide}$ and $t_{\rm enc} < t_{\rm tide}$.
  - In the case of a slow encounter, work out the "tidal radius".
  - For an isothermal halo, write down the "Roche criterion" for *slow encounters*. What does this criterion imply for stars outside the tidal radius?
  - Why does the formula for the tidal radius (4.6) only apply to the pericenter of an elliptical galaxy orbit?
  - Work out the absolute change in energy per unit mass as well as the relative change in energy for a *rapid encounter* and discuss the dependencies on interaction velocity and stellar densities of both systems.

- **Dynamical Friction.**
  - Explain the physics of dynamical friction via a thermodynamical equilibrium argument and if you consider the interactions in the rest system of the heavy galaxy. *Bonus:* Does this effect also work for a charged particle (e.g., a proton) moving through an electron-proton plasma?
  - Derive the Chandrasekhar formula for the mass loss rate of a galaxy moving through a cloud of light particles.
  - Can we measure the dark matter particle mass from the energy lose rate of a galaxy due to dynamical friction?
  - What happens to galaxies of different masses orbiting in a galaxy cluster over long time scales?
  - Derive Stokes friction from Chandrasekhar's formula. In which limit does this apply?
  - Derive the decay of a galaxy orbit through dynamical friction. To this end, please assume a circular orbit for the galaxy in a cluster that is described by the singular isothermal sphere model. Use this result to argue which galaxies can sink to the cluster center over the age of the universe.
- **Ram Pressure Stripping.**
  - Derive the condition for ram-pressure stripping.
  - Which types of galaxies are effected by ram-pressure stripping: spiral or elliptical galaxies?
  - What is the observational consequence of ram-pressure stripping?
  - Does ram-pressure stripping work more effectively in cosmic filaments or in galaxy clusters?
- **Virial Theorem.**
  - Derive the virial theorem in Eq. (4.58) by considering N galaxies in a Newtonian potential that move according to the Newtonian equations.
  - Summarize the main assumptions behind the derivation of the virial theorem and check how well they are fulfilled in practice.
  - Weigh a cluster with galaxies to order of magnitude. To this end, please adopt a cluster radius $R_{\rm cl} \sim 1$ Mpc, a galaxy velocity dispersion in a cluster, $v_{\rm cl} \sim 1000$ km s^{-1}, and $N_{\rm gal} \sim 200$ cluster galaxies with radius $R_{\rm gal} \sim 3$ kpc and rotation velocities $v_{\rm gal} \sim 150$ km s^{-1}.
  - How would you need to modify the sizes of the galaxies in order to explain the cluster mass without dark matter?