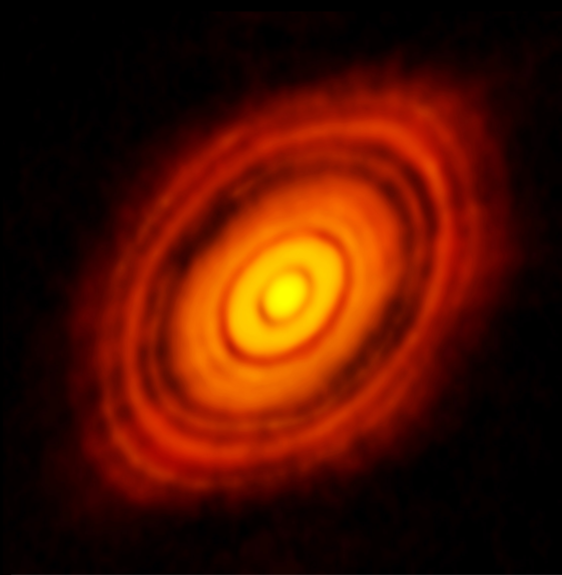
PLANET – DISK INTERACTIONS



SUMMARY.
Planets form in protoplanetary disks around young stars, like the one around HL-Tau imaged by ALMA shown on the adjacent picture. Such disks are mainly made of gas, with $\sim 1\%$ dust, from which planets grow. As a consequence, planets must interact with the gas while they form. Actually, the structures seen on the image may be due to planets in formation. In turn, the perturbed disk acts on the planets, which leads to a modification of their orbits : they migrate !
Migration is a key ingredient in planet formation. The strong variety of extra-solar systems can not be explained without migration (in particular, the famous hot Jupiters can not have formed so close to their star, they must have migrated inwards). In this METEOR, we will explore the theory and the various applications of planet-disk interactions.

OBJECTIVES

- The students will be taught how to use a hydro-dynamical code, launch simulations for various set-ups, analyse the output, and interpret the results.
- They will learn the basic equations governing the physics of proto-planetary discs and planetary migration. The numerical method to implement these equations into the code will be presented.

PREREQUISITES

Fundamental courses linked/coming in support to this METEOR :
- Dynamics and Planetology
- Numerical methods
- Fluid mechanics

THEORY

by A. Crida, with E. Lega and H. Méheut

I) Disk structure
- Rotation rate and vertical structure.
- Aspect ratio, thermal balance.
- Viscous torque and evolution.

II) Spiral wake and Lindblad resonances
A planet perturbs gravitationally the axisymmetric disk and creates a spiral wake (see figure).
- Structure of the spiral.
- Expression of the one-sided torque.
- Negative total wake torque.

III) Type I migration
- Migration timescale.
- Corotation torque.
- Possible outward migration.
- Role of the disk structure, discussion on possible migration scenarios.

IV) Fluid mechanics
- Conservation laws. General considerations ; mass, momentum and energy conservation.
- Compressible and incompressible fluid.
- Euler equations in cylindrical coordinates, case of a proto-planetary disk.
- Ideal gas and first law of thermodynamics

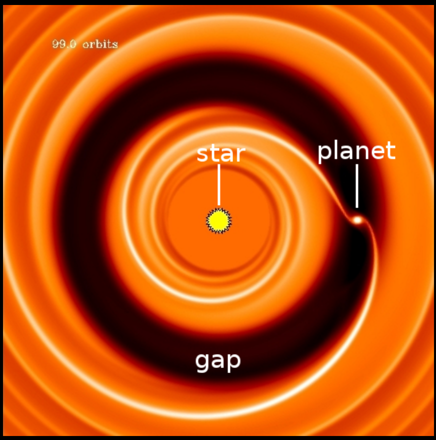
V) Numerical scheme
- Finite difference methods.
- Introduction and tutorial to the FARGOCA code.

APPLICATIONS

by A. Crida, with E. Lega and H. Méheut

The students will perform numerical simulations using the existing code FARGOCA, producing density maps like the one below.

In order to get familiar with the code, the students will first perform a numerical simulation with 1 planet on a fixed circular orbit, and study its influence on the disk over a dozen of orbits. A spiral wake appears, which will be compared with the theoretical shape of the wake seen in the lectures and example classes. Together, the students will decide on a strategy to explore the parameter space and run additional simulations to test the validity of the theoretical model.



The students will then perform individual projects, based on recent research in the field of planetary migration. Possible topics are :

- Eccentric planet.

Study the effect of e on the wake. Study the effect of the disk on the planet, in terms of expected migration speed and eccentricity evolution. Release the planet and compare.

- Fourier series and resonances.

All the variables of the problem can be decomposed in Fourier series along the azimuth coordinate. Implement only 1 mode of the planetary gravitational and study the response of the disk. Compare with the Fourier decomposition of the spiral wake. Discuss the link with Lindblad resonances.

- Torque map.

The total torque felt by the planet comes from various regions of the disk. A torque map reveales interesting structures, if normalized, folded, and treated appropriately. The contribution of each elementary ring is also of interest and can highlight the corotation torque.

- Inclined planet and 3D effects.

Simulations in 3D with a planetary orbit inclined with respect to the disk midplane. How does the inclination and the migration rate vary under the influence of the disk? Discussion of the role of the smoothing of the potential.

- Resonances.

Simulations with multiple planets in convergent migration. Under which condition do they get captured in mean motion resonance? Which type of resonance if favored?

- Type I migration

Study the torque felt by the small mass planet on a fixed circular orbit as a function of the various disk parameters. Compare with the theoretical formula. Release the planet and check. One may build a disk with a zero torque radius.

This project list may be appended, to include topics of interest connected to the research projects of the planetary science team (e.g. gap opening giant planets, double planets...).

MAIN PROGRESSION STEPS

- First two weeks of the period : theoretical courses in the morning, example class in the afternoon.
- Rest of the period : numerical project.
- Last week : preparation of the final oral presentation.

EVALUATION

- Written exam based on the theoretical lectures (30%), typically in the 3rd or 4th week.
- Mark from the supervisors (30%), based on our interactions during the METEOR.
  A curious and scientific, open but rigorous attitude will be appreciated. The autonomy of the students will be estimated, keeping in mind that the purpose of this METEOR is to train them. We will evaluate how deep the students understand their project, and how fast and far they move on with it.
- Final presentation of the individual projects (40%).

BIBLIOGRAPHY & RESOURCES

- Review on planetary migration at the 2013 *Protostars and Planets VI* conference :

Video of the presentation.

Book chapter.

- Lecture by F. Masset on planet-disc interactions : abstract ; pdf.

CONTACT

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