AST 501 - Fundamentals of Planetary Science I
Formation of Planetary Systems

Course Information:

- **Class Times:** M/W/F 11:30 – 12:20 pm
- **Location:** Physical Sciences, Rm 111
- **Instructor:** Dr. Diego J. Muñoz
  - email: diego.munoz@nau.edu
  - Office: Physical Sciences 319/320
  - Office hours: M at 1:00-2:00 PM and W at 1:00-2:00 PM by previous appointment

Course Description: This graduate course provides an in-depth exploration of the current state of knowledge in the field of planet formation theory. Students will examine the physical processes and observational evidence that inform our understanding of the formation and evolution of planets and planetary systems. Topics covered include the formation of protoplanetary disks, the growth of planetesimals and planetary embryos, the assembly of planetary systems, and the dynamical evolution of planets and their orbits.

Learning Objectives: • Understand the physical processes that govern planet formation • Gain knowledge of the observational evidence that informs planet formation theory • Develop an understanding of the mathematical models used to simulate planet formation • Analyze the major theories and hypotheses of planet formation • Explore the current state of knowledge in the field of planet formation • Critically evaluate scientific research in planet formation

Textbooks:
–"Astrophysics of Planet Formation" by Phillip Armitage (Cambridge University Press). This book is available at Cline library (1 copy and online access)
–"From Dust to Life: The Origin and Evolution of Our Solar Sytem" by John Chambers and Jacqueline Mitton (Princeton University Press). This book is not available at Cline, but the instructor's copy can be borrowed directly from him.

Additional Resources:
–"Planetary Sciences" by Imke de Pater & Jack Lissauer (Cambridge University Press)
– "Evolution of the protoplanetary cloud and formation of the earth and planets" by V.S. Safronov
– "Radiative Processes in Astrophysics" by G. Rybicki & A. P. Lightman (Wiley)

Contents and Tentative Schedule

PART I: Protoplanetary Disk Physics (4 weeks)
PART II: Protoplanet Formation and Growth (5 weeks)
PART III: Early Evolution of Planetary Systems (4 weeks)

- **Week 1**: Introduction to Planet Formation Theory

  • Introduction to the course and overview of planet formation • Historical overview and the planet formation hypothesis • The Kant-Laplace proto-Solar Nebula Hypothesis • The minimum-mass Solar Nebular • Planet formation thoroughout the Galaxy • Physical processes and timescales of planet formation • Observational constraints on planetesimal and embryo growth

- **Week 2**: Protoplanetary Disks as Astronomical Sources

  • The concept of infrared excesses and early evidence of disks around young stars • Review of black-body radiation and radiation transport • Simple models of protoplanetary disks • Morphology and spectral energy distribution of protoplanetary disks • Properties of real protoplanetary disks

- **Week 3**: Protoplanetary Disks as Multi-Species Fluids

  • Role of dust in disk observable properties • Dynamics of disk gas and dust • Hydrodynamics drag and radial drift of dust grains • Dust settling • Streaming Instability • Dust Coagulation

- **Week 4**: Long-term Evolution of Protoplanetary Disks

  • Protoplanetary disks are accretion disks • Nature and consequence of accretion disk viscosity • Protoplanetary disk turbulence • Viscous spreading of accretion disks • Disk dispersal and photoevaporation • Transitional disks

- **Week 5**: Formation of Planetesimals and Planetary Embryos in Protoplanetary Disks

  • Growth mechanisms of planetesimals • Formation of planetary embryos • Role of planetesimal and embryo dynamics in planet formation

- **Week 6**: Laboratory Experiments on Planet Formation • Two-body collisions • Dust aggregate collisions • The Princeton MRI experiment

- **Week 7**: Terrestrial Planet Formation

  • Accretion of planetesimals and embryos • Differentiation and core formation • Late stage collisions and the Moon-forming impact • Constraints on terrestrial planet formation from the Solar System and exoplanetary systems

- **Week 8**: Giant Planet Formation

  • Core accretion and gravitational instability models • Role of planetesimal and embryo dynamics in giant planet formation • Observational constraints on giant planet formation

- **Week 9-10**: Late Stages of Planet Formation and Early Orbital Evolution of Planetary Systems

  • Overview of Orbital Dynamics • Giant Impacts • Orbital resonances and stability • Planetary migration and eccentricity pumping/damping • Dynamical evolution of planetary systems • Long-term stability of planetary systems

- **Week 11**: Testing Planet Formation Theory with Exoplanet Demographics

  • Techniques for exoplanet detection • Properties of exoplanets and exoplanetary systems • Implications for planet formation theory

- **Week 12**: Formation and Sculpting of the Solar System

  • The Formation of Asteroids and Comets • The origin and composition of meteorites • Compositional diversity and implications for formation theories • Early evolution of planetary orbits • The Late Heavy Bombardment Hypotyhesis and its implications for Solar System history • Formation and Dynamics of the Kuiper Belt • The formation and evolution of the Moon

- **Week 13**: Current Topics in Planet Formation Theory

  • Recent advances and discoveries in the field • Unsolved problems and future directions • Critical evaluation of research in planet formation

- **Weeks 14-15**: Final Project Presentations

  Students will work on a final project, which may involve a literature review, original research, or a presentation on a specific topic in planet formation theory.

Lecture Format: Lectures will involve active discussions based on the reading materials assigned in advance. Discussions will led by the instructor, fostering active engagement from students. While the lectures will include some mathematical derivations and formal presentations on technical subjects, students will be consistently encouraged to contribute their thoughts and insights. Student participation will be graded.

Grading:

Participation	30%
Problem Sets	40%
Theory Project	10%
Final Presentation	20%

Final letter grades will be assigned according to:

A = 90 – 100. B = 80 – 89. C = 70 – 79. D = 60 – 69. F = 0 – 59.

Attendance and participation (individual): While formal attendance is not compulsory, students' involvement throughout the semester will contribute to a grade that mirrors their engagement. Feedback on participation will be provided to each student at various intervals during the duration of the course.

Weekly readings (individual): Students should anticipate reviewing the pertinent materials for the upcoming week's discourse beforehand. The instructor will furnish the reading materials no later than the Friday of the preceding week. Supplementary, discretionary reading materials on more advanced topics will also be accessible.

Problem sets (in groups): There will be three problem sets aligned with the course's three primary modules. These problem sets offer the option for collaborative work in groups of up to three students. The solutions should be presented in the format of a "scientific paper." Evaluation of these papers will take into account both their content and writing quality with equal weight. Any additional credit problems will be graded on an individual basis.

Theory Project (individual): "Pen and paper" theory is accessible to all advanced students and scientists. To prove this point, and to demonstrate reproducibility in the research process, students are expected to find a theory paper on any sub-topic of interest within the areas of planet formation, planetary evolution and dynamics. Once the selected paper is vetted by the instructor, the student will read the paper, reproduce (in a theory-based write-up) the key working expression from the paper, and will also re-create a key figure/plot from the paper.

Final Projects (in groups): Students, working in groups of up to 3, will select a topic of interest related to planet formation, planetary evolution, and dynamics. The selected topic will be pitched to the class in a brief presentation (no slides) on Week #6 of the course. Students will perform a literature review on this topic, and will produce a (minimum) 15-page (double-spaced, not including figures or references) review paper on the topic. This material will then be distilled into a 20-minuted colloquium-style review talk given to the class at the end of the semester.

Course Policies:

- Collaboration with peers on assignments is encouraged. Credit should be given to all collaborators, either through co-authorship or by citing personal communications. Plagiarism in written work will be not be tolerated, resulting in a failing grade for the assignment and, potentially, referral to the University. See policy.nau.edu/policy/policy.aspx?num=100601 for NAU's policies on academic integrity.
- Homework and article write-ups are due by 11:30 am on Friday (**before class**). Late assignments will be accepted within a 7-day window, incurring a deduction of 10% in points for each day they are overdue. Should you anticipate being unable to meet a deadline or deliver a presentation, kindly reach out to the instructor at your earliest convenience.

Important Dates:

Select a theory paper to reproduce .... Sep 29
Problem set #1 due .... Oct 6
Pitch review topic to class .... Oct 13
Problem set #2 due .... Nov 3
Review paper outline due .... Nov 17
Problem set #3 due .... Dec 1
Group presentations .... Dec 4-8
Review paper due .... Dec 8