**Planet-Forming Collisions** – PTYS 595B, Spring 2021

Tu,Th 12:30 to 1:45pm – online meetings

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**Approach and scope.** This course is not just about collisions (cratering, physics of shocks, geophysics under intense loads and rates) but also how these collisions shape the formation of planets by bringing matter together into one place, from pile-ups of pebbles to giant impacts, and by eroding or destroying planetary bodies after they've formed. Understanding planet formation requires a basic knowledge of these diverse processes, and this requires an equal measure of astrophysics and planetary geophysics, so that is our approach.

Topically *Collisions* is divided into four parts, though not in sequence: (1) impact physics; (2) planet formation theory; (3) the geology of collisions; and (4) biases. The first two may be reviews for some students. Geology refers to craters and their landforms, but also global-scale imprints such as bilobate shapes, layered structures and 'splats', impact-triggered differentiation, and so on. The latter refers to the various ways in which the observed record (through astronomy and missions and meteoritics) biases our understanding of planet formation. Are the terrestrial planets and their satellites representative of the starting population? Nearly all of the smaller bodies were accreted or ejected during planet formation; what does this imply for the remainders? How are cratered landscapes biased by overprinting and relaxation? Can we ever know if a planet had more than one giant impact? Meteorites are famously biased, being fragments of bolides, themselves fragments (of fragments) of original asteroids, that disrupted during atmospheric entry, and have been recovered and have survived the surface conditions of the Earth. Can sample return missions unravel these biases? Can exoplanetary observations? Theory?

**Course objectives.** Students will become familiar with the physical process of impacts and collisions, and with the collisional dynamics of planet formation. They will become well-versed in the prevailing modern theories, and understand the controversies by reading and discussing the current literature. They will become expert in one area of research by leading discussions and presenting on a focus topic.

**Course outcomes.** Upon completion of this course students will be able to apply quantitative reasoning to research questions about impact cratering, catastrophic disruption, and giant impact accretion, from planet formation to surface landform evolution. They will understand the heritage of ideas as that have developed over the past 50 years, in these interconnected disciplines.

**Required readings.** The required textbook is Melosh, *Impact Cratering: A Geologic Process* and copies may be obtained from the instructor since the book is long out of print. The scope of *Collisions* differs from impact cratering in being more astrophysical. One might define an impact as a projectile, however large, hitting a much larger target, so that the event is impulsive on the gravitational timescale, whereas a collision involves global-scale processes, the key difference being the interaction is long compared to the gravitational timescale. This means that a giant impact is a collision, the best-studied example being the origin of the Moon; so are the binary accretions of small bodies into ever-larger ones in the first millions of years. These fields of study are full of surprises, and novel observations, and new (and often wrong) theories, so in addition to the textbook we shall rely extensively on readings from the literature.

Students are responsible for providing the readings relevant to their discussion by emailing the class and uploading to the box folder in PDF format <u>two days in advance</u> of the discussion.

**Format.** We will meet by zoom most days. If we are discussing a paper, we can also make use of audio calls for discussions where voice duplexing is superior (easier to talk at once and interject with questions). The first five weeks will be mostly lectures, ending with the exam. The next five weeks will be discussions led by the instructor interleaved with student project first discussions. The next five weeks will continue in discussion-seminar format, mostly led by students in their second discussions, where they will also introduce their draft 2-page abstracts for feedback. The final two weeks will end with project presentations, where students give either a review lecture or an original-research lecture (at a suitably advanced level, reflecting the class discussion) and submit their finished abstracts.

**Grades.** A=90-100%, B=80-89.9%, C=70-79.9%, D=60-69.9%, F<60%. The midterm covers the introductory lectures and readings and is comprehensive and quantitative. Rewrites are allowed for half credit, so a student who gets 70% on the exam and does a correct rewrite gets 85% or B, so could still get an A in the course. There is no final exam. The final project culminates in a reviewed, referenced research abstract (2-pages) plus a 30-minute presentation. Students will also lead two discussions on papers or abstracts related to their project, and their topic can evolve during the course of these discussions. The project grade (40%) is based on the preparation and management of the discussions, the organized dissemination of materials, the rigor of the scientific approach, the quantitative basis of the analysis, the clarity and completeness of the 2-page research abstract, the academic completeness of the presented background materials, and the student's ability to field questions.

- 30% - midterm exam (end of week 5)
- 30% - daily preparation for lectures and discussions; homework problems
- 40% - final project (week 6-15)

Daily preparation includes carefully reading the required assignments. You can't get a good grade if you don't study the readings; plus it drags down the class when one student is unprepared. If preparation is overall inadequate there will be a pop quiz to be factored in to the daily preparation grade.

**Project:** Project topics can be anything that is relevant to the study of planet-forming collisions. You can review a topic in depth, or can present your original research. You are encouraged to try something new; you certainly won't be penalized for naivete. You can present a spin-off of your thesis research, but the expectation will be proportional.

Beginning in week 6 students will take turns leading a discussion on their topic, and will get feedback after the discussion regarding their proposed research project. Examples include:

- Collisional formation of asteroid families
- Dynamical evolution (*N*-body) of late stage planet formation
- Moon and satellite formation by collisions
- Shock thermodynamics of rocks, ices and/or oceans
- Signatures of giant impacts on Mars, Pluto, Haumea…
- Regional and hemispheric collisions
- Meteorites or samples as a record of collisional processes
- Impact experiments related to planetary science

- Impact research facilities, technologies and capabilities
- Numerical simulations of collisions
- Impacting space missions (e.g. Ranger, Deep Impact, LCROSS, Hayabusa2, DART)

**Class policies**:

- Make an office hour request after class, or by email.
- Regular attendance is vital for an interactive class. If you miss a class, it is your responsibility to get notes from your fellow students, and if a recording is available, to listen to the lecture.
- For university-approved activities for which you have in advance a note of Dean's approval, you will be excused, or other arrangements will be made. If you will be absent due to a religious holiday, please let me know by email one week in advance. Absences for other reasons will not be excused unless special dispensation was received in advance.
- Assignments are due at the beginning of class on the due date. If an assignment is due, you are responsible for turning it in, even if you are absent from class. Late work will not be accepted unless arrangements are made prior to the due date.

**Academic integrity**:

- You are expected to know and to abide by the University's Academic Integrity policy, http://deanofstudents.arizona.edu/codeofacademicintegrity. Academic Integrity is expected of all students in all examinations, papers, laboratory work, academic transactions and records.
- You may work together on any of the homework assignments, except for the midterm rewrite, but make a dedicated attempt to solve it yourself first.
- You are encouraged to discuss the structure and content of your final project with other students, getting stylistic help and advice on presenting, but any evaluated material must be your work and your work only. *Previously completed class projects or research projects may not be submitted for final project credit.*

**Nondiscrimination and Anti-harassment Policy:**

- The University of Arizona is committed to creating and maintaining an environment free of discrimination. In support of this commitment, the University prohibits discrimination, including harassment and retaliation, based on a protected classification, including race, color, religion, sex, national origin, age, disability, veteran status, sexual orientation, gender identity, or genetic information. For more information, including how to report a concern, please see: http://policy.arizona.edu/human-resources/nondiscrimination-and-anti-harassment-policy

**University Policies**

- https://academicaffairs.arizona.edu/syllabus-policies

**Subject to Change Notice**

- Information contained in the syllabus, other than the grade and absence policies, may be subject to change with reasonable advance notice, as deemed appropriate by the instructor.

**Graduate Student Resources**

- http://basicneeds.arizona.edu/index.html

**COURSE SCHEDULE:** Lecture topics may be modified depending on the backgrounds, capabilities and ambitions of the students who are enrolled, as well as by the availability of guest lecturers or discussion participants, and unforeseen research/project/service absences by the instructor.

**COURSE MATERIALS:** **https://arizona.box.com/s/vna7p5bp34sp2yilwzb4n84vy1np1oxx**

**Week 1 – Th 1/14**
Discussion of syllabus; current events; project topic ideas and interests

*Readings due Tu 1/15: Shoemaker (1963), Armstrong et al. "Rummaging…" (2002)*
*Homework due Tu 1/15: Derive a formula for the average impact angle for a random-velocity-vector particle hitting a spherical planet, without consideration of the planet's gravity. For extra credit, include consideration of the planet's gravity.*

**Week 2 – Tu 1/19, Th 1/21**
Lecture: Introduction to shocks, from B. S. Wright *Shockology* notes
Lecture: Impact cratering and its consequences
Discussion: What does impact crater scaling mean?

*Reading due Tu 1/22: Zahnle (2007) "Emergence of a habitable planet"*
*Reading due Th 1/24: Melosh 2&3; O'Brien et al. 2018; Chambers 2014*

**Week 3 – Tu 1/26, Th 1/28**
Lecture: Stress waves; equations of state
Lecture: Elastic solids, fragmentation and friction

*Reading due Tu 1/29: Melosh Chapters 5 and 7*
*Homework due Th 1/31: Select three candidate papers for your project idea, two background papers and one focused topical paper. (One of these will probably be the paper you hand out for your seminar. You aren't bound to these.) Email to me before class the links to each paper. For the bakground papers, write a 100-300 word description of why you think it is good background reading.*

**Week 4 – Tu 2/2, Th 2/4**
Lecture: Large impact structures on the Moon and planets

*Reading due Tu 2/5: Asphaug et al. (Asteroids IV, 2015) "Global Scale Impacts"; Barr "On the Origin of Earth's Moon" (2016)*
*Homework due 2/7: Disruption estimation*

**Week 5 – Tu 2/9, Th 2/11**
Lecture: Scaling of crater dimensions
Lecture: Case studies in similar sized collisions

*Homework for 2/12: prepare for Midterm Exam*
*Homework for 2/14: Chambers (2013) or similar paper*

**Week 6 – Tu 2/16, Th 2/18**
2/12: Midterm Exam

2/14: Midterm Solutions; Lecture: Theories of planet formation

*Homework for 2/23: Come up with a one-paragraph project idea plus bibliography. The project idea, you can iterate with me by email beforehand and solicit ideas from colleagues and faculty. The bibliography shall include 3 background papers that you have read. For each of these papers, provide one or two sentences for each, why it would be a good background paper for a topical discussion related to your project idea. I will select one of those three papers for you to discuss at a later date, choosing in part so we have a well-rounded set of papers as a class.*

**Week 7 – Tu 2/23**
*Reading for 3/2: Artemieva and Lunine 2003*

**Th 2/25 READING DAY (no class)**

**Week 8 – Tu 3/2, Th 3/4**
Large impact structures; similar-sized collisions

**Tu 3/9 READING DAY (no class)**

**Week 9 – Th 3/11**
*Melosh Chapter 9, 10*

**Tu 3/16, Th 3/18**
*NO CLASS – Lunar and Planetary Science Conference*

**Week 10 – Tu 3/23, Th 3/25**
LPSC Abstracts, take turns with presentation and analysis

**Week 11 – Tu 3/30, Th 4/1**
Lecture: computer modeling
Student-led seminars

**Week 12 – Tu 4/6, Th 4/8**
Student-led seminars

**Week 13 – Tu 4/13, Th 4/15**
Student-led seminars

**Week 14 – Tu 4/20, Th 4/22**
Student Lectures
*Reading for Th 4/25: Asphaug 2018, Planetesimals; Elkins-Tanton 2018*

**Week 15 – Tu 4/27, Th 4/29**
Student Lectures
Lecture: Accretion of planetesimals and the Psyche mission

**Week 16 – Tu 5/4**
Last day of class