# Planet-Forming Collisions

SYLLABUS – PTYS 595B – Spring Semester 2019 – Tu & Th, 2:00-3:15pm – Kuiper 301/312

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**Scope.** The prevailing wisdom is that Mars-sized planets accreted first ("oligarchic growth") and went on to merge sequentially in a "late stage" of giant impacts, involving colliding bodies that had grown to being comparable in size. Terrestrial planetary accretion, measured as mass per unit time, was dominated by this stage, giant impacts happening sequentially, leaving remnants such as the Moon.

*This course is towards a careful understanding of that process and its implications: the dynamics, the collisions, and the consequences for planetary identity*. The course begins with cratering-related physics and science, and moves on to the topic of collisions involving pairs of bodies within a factor of about 10 in mass and 2 in size, the mass ratio $\gamma = M_2/M_1$, where the collision velocity is "self-stirred", that is, within a few times their mutual escape velocity $v_{esc}$.

When $\gamma \lesssim 0.001$ the target is effectively a half-space for most collisions at these speeds, and most impacting material is retained. (This is <u>not</u> true when impact speed is many times the escape velocity, as is the case for comets impacting the Moon for example). The Chicxulub impact added a millimeter to Earth's radius ($\gamma_{KT} \sim 10^{-9}$). The event that formed the SPA basin on the Moon was $\gamma \sim 10^{-3}$, still a cratering event, although here the projectile was 10% the size of the Moon and would have overlapped the limb, for nominal impact angles. For this mass ratio a 30° (measured from vertical) impact starts to look oblique in terms of the projectile continuing downrange as it interacts with the target.

For half-space cratering, simplifying assumptions apply, and the process is closely analogous to point-source explosions. Most impact cratering events can be adequately modeled in 2-D, and the gravity field is simply $g = g_z$=constant, so a lot of research is possible using simple analytical forms, and using simulations at much higher spatial and time resolution than in 3-D.

Due to the monomodal sizes of oligarchic growth, the peak rate of terrestrial planetary accretion takes place for $\gamma$ from a few % to more than 50%. For these similar-sized collisions (SSCs, which include giant impacts) the same physics of impact cratering applies – shock physics and rock mechanics and so on – but now there is an astrophysical aspect to the problem, the primary consideration of self-gravity and angular momentum. Similar sized collisions are fully 3-D, and a point-source is no longer a good analogy, and axisymmetric 2-D models are inappropriate. There is no impact locus, and gravity is neither 'down' nor is it constant.

"Small giant impacts" are a subcategory of SSCs that possibly relate to the origin of major objects like Vesta and Psyche and Haumea, including large satellite-satellite collisions and possibly the origin of Titan. What makes them small, is that the collision velocity is slower than the sound speed, so there are no shocks. The impact physics changes at smaller than 100-1000 kilometer scales, to a regime dominated by rheological behavior such as friction. This regime is very poorly understood.

Despite almost four decades of research, there is not yet any systematic understanding of giant impacts, the way there is for impact cratering. It is now known that half of giant impacts do not result in accretion (hit and run collisions), leading to questions of solar system dynamics, so in addition to studying collisions and their aftermath, we will also review the topic of N-body accretion and some modern theories of solar system formation.

**Format.** The first five weeks of the course will be mostly lectures by the instructor, ending with the only exam. (My tradition is that the midterm will be challenging, and you can do re-writes for half credit, e.g. if you get an 80% on the midterm and 100% on the rewrite you will get 90%.) The next five weeks will be discussions of current readings led by the instructor (and may include one or two guest lectures from expert colleagues). The next five weeks will continue in the discussion-seminar format, except that students will each lead a 45 minute discussion about a paper serving as background to what will be your final project – you will distribute the discussion materials ahead of time and come prepared to lead the discussion. The final two weeks you will present your final projects, giving a 30 minute review or original-research lecture. (Your discussion-seminar will have provided the background, so it should be at a high level.) Due to research and committee obligations there will be no class for two of the scheduled weeks; you will work on your projects and I will arrange for online hangouts.

**Grading.** Your grade will consist of three components. The midterm exam will cover the introductory lectures. For all of the discussions, you will be graded on preparedness and participation. For the discussion that you lead, related to your final project, you will be graded on your ability to prepare for and manage a group discussion. For your final project, you will be graded for rigor, clarity, quantitative basis, academic completeness, and ability to field questions. There will be no final exam.

- 30% of your grade will be from the midterm exam
- 30% of your grade will be course participation
- 40% of your grade will be the review lecture and final paper

**Project:** Your project topic can be anything that is relevant to the study of planet-forming collisions. You can review a topic, or you can present your own research. You are encouraged to try something new that is a bit beyond your comfort zone; you certainly won't be penalized for this. If you wish to present a spin-off of your thesis research that is also OK but the expectation will be proportional.

- Formation of contact binary comets and KBOs
- Collisional formation of asteroid families
- Dynamical evolution (*N*-body) of late stage formation
- Moon and satellite formation by collision
- Shock thermodynamics of rocks and ices
- Signatures of giant impacts on Mars, Pluto, Haumea, etc.
- Regional-scale and hemispheric-scale collisions
- Meteorites or lunar samples as a record of collisions
- Impact experiments
- Numerical simulations
- Missions and studies involving impacts (Deep Impact; LCROSS; Hayabusa 2; DART)

**Class Policies**:

- Office hours before class, by appointment
- Regular attendance is vital. If you miss a class, it is your responsibility to first, get notes from fellow students, and then, to schedule with me to go over anything specific.

- 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, let me know by email one week in advance. Absences for other reasons will not be excused unless special dispensation was received in advance.
- Your class participation grade includes preparing adequately for class by carefully reading the required assignments. You can't get a good grade if you don't study the reading; plus it drags down the class when someone is unprepared. Although I don't anticipate the need, if it appears that preparation was inadequate, I will give a pop-quiz to be factored into the class participation grade.
- 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 may be called on to explain your answer and its derivation to the class.
- 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.*

**Students with Disabilities:**

- At the University of Arizona we strive to make learning experiences as accessible as possible. If you anticipate or experience physical or academic barriers based on disability or pregnancy, you are welcome to let me know so that we can discuss options. You are also encouraged to contact Disability Resources (520-621-3268) to explore reasonable accommodation. The accessible table and chairs in Room 312 will remain available for students who find that standard classroom seating is not usable.

**Revision of the Syllabus:**

- This is a topical graduate class, so the syllabus will be modified depending on the backgrounds and capabilities of the students who are enrolled, and the availability of relevant experts who can participate in our discussions.
- Course workload and course requirements (i.e., content, reading materials, and the structure of graded assignments) are subject to change, with reasonable advanced notice, as deemed appropriate by the instructor.

**Syllabus:** Weeks are shown, with any absences or breaks indicated. *Homework* is shown for the following week in italics. Reading ahead is encouraged, and bonus points for bringing good and/or new publications or information to the attention of the class. Please let me know about errata.
*This document is subject to revision and will be updated as necessary in class.*

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

**Week 1 – Th 1/10**
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. (a) Without consideration of the planet's gravity, e.g. pre-encounter velocity >> $v_{esc}$. (b) With consideration of the planet's gravity, e.g. pre-encounter comparable to $v_{esc}$.*

**Week 2 – Tu 1/15, Th 1/17**
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, Appendix I, II: Hugoniot Relations, Equations of State*
*Homework due Th 1/24: Revisit Armstrong et al. (2002): quantitative assessment of the paper*

**Week 3 – Tu 1/22, Th 1/24**
Lecture: Stress waves; equations of state
Lecture: Elastic solids, fragmentation and friction

*Reading due Tu 1/29: Melosh Chapters 4 and 5*
*Reading due Th 1/31: Gladman et al. (2005)*

**Week 4 – Tu 1/29, Th 1/31**
Lecture: Large impact structures on the Moon and planets

*Reading due Tu 2/5: Melosh Chapters 6 and 7; Benz 1990 theory of hydrocodes*
*Homework due 2/7: Disruption estimation (=midterm question from last time)*

**Week 5 – Tu 2/5, Th 2/7**
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 2/12, Th 2/14**
2/12: Midterm Exam
2/14: Midterm Solutions; Lecture: Theories of planet formation

*Homework for 2/19: Asphaug (2010), Canup et al. (2019)*

**Week 7 – Tu 2/19, Th 2/21**

*Reading for 2/26: Artemieva and Lunine 2003, Asphaug 2010*

**Week 8 – Tu 2/26, Th 2/28**
Large impact structures; similar-sized collisions
*Reading for 3/12: Melosh Chapter 9, 10*

*Homework for 3/12: 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.*

**UA SPRING BREAK**
**2/30 – 3/10**

**Week 9 – Tu 3/12, Th 3/14**
Lecture: computer modeling
Student-led seminars

**Week 10 – Tu 3/19, Th 3/21**
*NO CLASS – Lunar and Planetary Science Conference, Houston TX*
*Online hangout on 3/21*

**Week 11 – Tu 3/26, Th 3/28**
*NO CLASS – Space Studies Board meeting in DC*
*Online hangout on 3/28 to discuss projects / papers*

**Week 12 – Tu 4/2, Th 4/4**
Student-led seminars

**Week 13 – Tu 4/9, Th 4/11**
Student-led seminars

**Week 14 – Tu 4/16, Th 4/18**
Student Lectures
*Reading for Th 4/25: Asphaug 2018, Planetesimals; Elkins-Tanton 2018*

**Week 15 – Tu 4/23, Th 4/25**
Student Lectures
Lecture: Accretion of planetesimals and the Psyche mission

**Week 16 – Tu 4/30**
*NO CLASS – Psyche Science Team Meeting, ASU*