AST3100 Astrophysical Transients

"You don't observe the same Universe twice"[1]

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Mondays 02:00 PM in AB113
Thursdays 11:00 AM in AB113
https://utoronto.zoom.us/j/81146947092 (see email for passcode)

Course summary

Astrophysical transients can be loosely defined as all celestial phenomena whose brightness varies significantly over timescales less than a human lifetime. They present us with both a mystery – to piece together their origin – and an opportunity – being unique probes or laboratories to better our understanding of (astro)physics. In this course we will explore the transient phase space and approaches to discovery, by studying select classes of transients (supernovae, gamma-ray bursts, magnetar flares and fast radio bursts) and their applications as examples. We will study the physics of disruptions and eruptions, their energy sources and timescales in a general framework to understand what sources might fizz, crackle and pop in the universe. Finally, we will discuss how technological advances play a role in discovery and we will try to identify opportunities for new discoveries.

Course goals

Students should get a better grasp of the history of discovery and how this has been aided by technological and theoretical advances. Students should get a better understanding of the connection between astrophysical transients and the open questions in (astro)physics they can address. Students should develop skills for reading research articles and presenting.

Prerequisites

Students are expected to have an understanding of undergraduate physics and astronomy, obtained through a formal degree in one of those fields or by other means. An understanding of stellar remnants, e.g., through AST1410H Stars will be useful. Homework assignments include exercises that require programming.

Course materials

Students will be assigned reading before each class from research articles that are freely accessible online or that will be made available by the instructor. Programming exercises will be based around open-source software packages. Typically, the first class of each week will be lead by the instructors to introduce the topic of the week, while during the second class of each week one or a few students will be assigned before class to present on and lead a discussion based on one of the assigned readings or homework assignments for that week. This in order to increase participation and encourage active learning, which has been shown to enhance retention of the material.

[1] Professor James Cordes, in a nod to Heraclitus.

Assessment

Students will be graded based on in-class presentations, homework assignments and a final project. During Weeks 1–2 students will give a presentation on a part of transient phase space (10%), during Weeks 3–4 students will make a homework assignment on calculating light curves (15%), during Weeks 5–8 students will give a presentation on an example class of transients (20%), during Weeks 9–10 students will make a homework assignment on binary star evolution that includes a small in-class presentation (15%). The course is concluded with a final project in Weeks 11–12 for which students write an observing/modeling/theoretical proposal (30%) that they will present in class (10%).

When students have to present, we ask that they discuss their presentation with instructors a few days before the actual class.

From auditing students we expect active engagement, but you are not required to hand in homework assignments or to do a final project.

1 Introduction to transient phase space and the history of discovery

Weeks 1–2

We will start this course by attempting to define the phase space of transients, in terms of their timescales and frequency/wavelength or messenger. We will then review how this phase space has been accidentally or deliberately charted up till now and how we can go about making inferences about the origins of transients. We will also discuss who gets to discover.

Key concepts: phase space, causality, disruption, eruption, chance coincidence probability, rates.

Week 1 Meeting 1 2022-09-12

Readings before class:

- Chapter 1 of text book "Relativistic Astrophysics of the Transient Universe" by Maurice H. P. M. van Putten and Amir Levinson, available online through the UofT library: `https://librarysearch.library.utoronto.ca/permalink/01UTORONTO_INST/14bjeso/alma991106479218006196`
- *Optional*: Table 1 of "The Caltech-NRAO Stripe 82 Survey (CNSS). I. The Pilot Radio Transient Survey In 50 deg^2" by K. P. Mooley et al. has a nice overview of slow transients, available through NASA/ADS: `https://ui.adsabs.harvard.edu/abs/2016ApJ...818..105M/abstract`

In class:

- Lecture by ZP on key concepts for this week.

Week 1 Meeting 2 2022-09-15

Readings before class:

- "An Education in Astronomy" by Riccardo Giacconi, available through NASA/ADS: `https://ui.adsabs.harvard.edu/abs/2005ARA%26A..43....1G/abstract`;

- "Little Green Men, White Dwarfs or Pulsars?" by Jocelyn Bell Burnell, available through NASA/ADS: `https://ui.adsabs.harvard.edu/abs/1979CosSe...1...16B/abstract`.

In class:

- Group discussion led by ZP on assigned readings.

Week 2 Meeting 1 2022-09-19

Groups of students pick a wavelength or messenger and present the phase space to the class. Questions that need to be answered are: What are the known sources? When were these transients first discovered? Why were they discovered then and could they have been discovered ealier? What are the gaps? Are the gaps due to a lack of technology or a lack of transients? What technological and theoretical advances will help us figure out the origin of these transients?

In class:

- Student presentations by TBD.

Possible references to base presentations on:

- *Optical*: Figure 1 from "Systematically Bridging the Gap Between Novae and Supernovae" by Mansi Kasliwal, available through NASA/ADS: `https://ui.adsabs.harvard.edu/abs/2012PASA...29..482K/abstract` (see also Figure 4 in `https://ui.adsabs.harvard.edu/abs/2007Natur.447..458K/abstract` for an earlier version);
- *Optical*: Figures 1 and 2 from "The Photometric and Spectroscopic Evolution of Rapidly Evolving Extragalactic Transients in ZTF" by Anna Ho et al., available through NASA/ADS: `https://ui.adsabs.harvard.edu/abs/2021arXiv210508811H/abstract`;
- *Radio*: Figure 1.2 from Evan Keane's PhD thesis "The Transient Radio Sky": `https://core.ac.uk/download/pdf/40032759.pdf` (see also `https://github.com/KenzieNimmo/tps` for a more up-to-date overview of pulsar and fast radio burst timescales);
- *Gravitational waves*: A web tool is available here, with links to a paper and blog post describing details: `https://faculty.wcas.northwestern.edu/cpb2759/GWPlotter/`.

Week 2 Meeting 2 2022-09-22

Same as last meeting.

In class:

- Student presentations by TBD.

2 Transient Observables

Weeks 3–4

We will discuss how the emission we see is produced, what sets the luminosity and timescale for transients, and the extent to which this relates to the underlying causes. The focus will be on the concept of a fireball, in which we see photons diffusing out of a hot expanding plasma ball.

Key concepts: shocks, fireballs.

Week 3 Meeting 1 2022-09-26

Readings before class:

- Section 13.1 from Arnett's "Supernovae and Nucleosynthesis", available at https://www-degruyter-com.myaccess.library.utoronto.ca/document/doi/10.1515/9780691221663/.
- If you have a favourite optical transient, what are the basic observed properties (luminosity, duration, expansian velocity, . . .)? What energy source powers it (radiative decay, jets, shocks, . . .)?

In class:

- Lecture by MvK.
- Discussion of transients described by a fireball.
- Discussion of energy sources that can power a fireball.

Notes at http://www.astro.utoronto.ca/~mhvk/transients22/2022-09-26-Notes.pdf

Week 3 Meeting 2 2022-09-29

Readings before class:

- Sections 13.3 and 13.4 from Arnett's "Supernovae and Nucleosynthesis", available at https://www-degruyter-com.myaccess.library.utoronto.ca/document/doi/10.1515/9780691221663/.

In class:

- Lecture by MvK.
- Discussion of what can cause extremes in supernovae.

Week 4 Meeting 1 2022-10-03

Readings before class:

- Sections 13.5 and 13.6 from Arnett's "Supernovae and Nucleosynthesis", available at https://www-degruyter-com.myaccess.library.utoronto.ca/document/doi/10.1515/9780691221663/.

In class:

- Lecture by MvK.
- Recombination and comparison with observed lightcurves.

Week 4 Meeting 2 2022-10-06

Readings before class:

- Up to Section 2.2.1 of "Early Supernovae Light Curves Following the Shock Breakout" by Nakar & Sari, available through NASA/ADS: https://ui.adsabs.harvard.edu/abs/2010ApJ...725..904N/abstract

- *Optional*: "Shock Breakout Theory" by Waxman & Katz, available through NASA/ADS: `https://ui.adsabs.harvard.edu/abs/2017hsn..book..967W/abstract` (from the "Handbook of Supernovae" edited by Alsabti & Murdin: `https://link.springer.com/referencework/10.1007/978-3-319-21846-5`)

In class:

- Lecture by MvK.
- Effects of shock breakout on supernovae lightcurves.

Homework assignment 1

Calculate a semi-analytic supernova light-curve.

Deadline: TBD

3 Examples

Weeks 5–8

We will take a deeper dive into the history and physics of four example classes of transients. In each week's second meeting students are asked to lead discussion based on assigned readings. The students are asked to discuss their interpretation of the literature and potentially some auxiliary material that they found with the instructors a few days before class.

3.1 Fast radio bursts

Why were fast radio bursts (FRBs) discovered in 2007? Do they all repeat? What observational constraints do we have and what are possible progenitors? What do we learn from the detection of FRB-like bursts from Galactic magnetar SGR 1935+2154? How can we progress the field?

Week 5 Meeting 1 2022-10-13

NB We're changing phase here to Thursday–Monday, because of the Monday holiday.

Readings before class:

- Sections 1–3 of review article "Fast radio bursts at the dawn of the 2020s" by Emily Petroff et al., available through NASA/ADS: `https://ui.adsabs.harvard.edu/abs/2022A%26ARv..30....2P/abstract`.

In class:

- Lecture by ZP.

Week 5 Meeting 2 2022-10-17

Suggested topics to discuss in more detail (please consult with ZP):

- FRB-like bursts from Galactic magnetar SGR 1935+2154 and bridging the gap between Galactic and extragalactic radio transients, based on, e.g., Chris Bochenek et al. (`https://ui.adsabs.harvard.edu/abs/2020Natur.587...59B/abstract`) and Ben Margalit et al. (`https://ui.adsabs.harvard.edu/abs/2020ApJ...899L..27M/abstract`);

- Possible models for explaining periodic activity in an FRB source: binarity, precession and slow rotation, based on, e.g., Paz Beniamini et al. (https://ui.adsabs.harvard.edu/abs/2020MNRAS.496.3390B/abstract), Dongzi Li & J. J. Zanazzi (https://ui.adsabs.harvard.edu/abs/2021ApJ...909L..25L/abstract) and Qiao-Chu Li et al. (https://ui.adsabs.harvard.edu/abs/2021ApJ...918L...5L/abstract);
- FRB host galaxies, based on one or more of Kasper Heintz et al. (https://ui.adsabs.harvard.edu/abs/2020ApJ...903..152H/abstract), Shivani Bhandari et al. (https://ui.adsabs.harvard.edu/abs/2022AJ....163...69B/abstract) and Alexandra Mannings et al. (https://ui.adsabs.harvard.edu/abs/2021ApJ...917...75M/abstract);
- Connecting FRBs to star formation, based on Clancy James et al. (https://ui.adsabs.harvard.edu/abs/2022MNRAS.510L..18J/abstract);
- Chance coincidences for associating FRBs with host galaxies or other transients (i.e., Figures 1–2 in https://ui.adsabs.harvard.edu/abs/2017ApJ...849..162E/abstract and §4.2 in https://arxiv.org/pdf/2208.00803.pdf).

In class:

- Discussion led by TBD on a more detailed topic picked by the students.

3.2 Magnetar flares

Week 6 Meeting 1 2022-10-20

Readings before class:

- TBD A text book chapter or review article on magnetar flares.

In class:

- Lecture by MvK.

Week 6 Meeting 2 2022-10-24

Readings before class:

- TBD Input for student presentation.

In class:

- Student presentation by TBD.

3.3 Gamma-ray bursts

Why were gamma-ray bursts (GRBs) discovered when they were discovered? What is the distance scale to GRBs debate and how was it resolved? What pieces of evidence led us to believe there are different classes of GRBs? How did we ultimately come to understand the sources of GRBs? What are the basic physical processes responsible for GRBs and their afterglows (jet models with forward/reverse shock, etc.)?

Week 7 Meeting 1 2022-10-27

Readings before class:

- TBD A text book chapter or review article on gamma-ray bursts.

In class:

- Lecture by ZP.

Week 7 Meeting 2 2022-10-31

Readings before class:

- TBD Input for student presentation.

In class:

- Presentation by TBD.

3.4 Supernovae

When were the first supernovae (SNe) discovered? How did we come to understand the source of SNe? What classes of SNe are currently known and what junctures can we identify in discerning that variety? What was the significance of SN 1987A? How can we understand basic properties of SNe, including differences between core-collapse and thermonuclear? This will likely based on Arnett's semi-analytic models that we have discussed in weeks 3–4.

Week 8 Meeting 1 2022-11-03

Readings before class:

- TBD A text book chapter or review article on supernovae.

In class:

- Lecture by MvK.

Week 8 Meeting 2 2022-11-14

Readings before class:

- TBD Input for student presentation.

In class:

- Student presentation by TBD.

4 Missing pieces

Weeks 9–10

We will explore the transient phase space and discuss what's left to discover and how technological advances play a role here. In week 9 we'll focus on single stars and compact remnants and in week 10 on binary combinations of stars and compact remnants. Some questions we will try to answer: What eruptions and eruptions can we expect from single stars or compact remnants? What is the biggest possible explosion (a pair-instability supernova)? Can we get bigger explosions from Population III instead of Population I stars (i.e., because with no metals you have no winds/mass loss)? What makes a transient maximally observable (e.g., in supernova the explosion energy is mostly unseen: adiabatic expansion cools the shocked material)? What types of transients are expected from binary combinations of stars and compact remnants? What binaries are dynamically stable and what binaries experience significant episodes of mass transfer?

Week 9 Meeting 1 2022-11-17

Readings before class:

- TBD One or two research articles that try to predict novel classes of transients.

In class:

- Lecture by ZP.

Week 9 Meeting 2 2022-11-21

Readings before class:

- TBD

In class:

- TBD

Week 10 Meeting 1 2022-11-24

Readings before class:

- TBC Chapter 3 of text book "An Introduction to the Evolution of Single and Binary Stars" by Matthew Benacquista, available online through the UofT libary: `https://librarysearch.library.utoronto.ca/permalink/01UTORONTO_INST/fedca1/cdi_springer_books_10_1007_978_1_4419_9991_7`.

In class:

- Lecture by MvK on binary stellar evolution.

Week 10 Meeting 2 2022-11-28

Readings before class:

- TBD

In class:

- TBD

Homework assignment 2

Pick a binary system, calculate its volumetric rate and run its evolution using COSMIC to check the dynamic stability, duration of mass transfer, etc.

Deadline: TBD

5 Exploring current and future transients

Weeks 11–12

Week 11 Meeting 1 2022-12-01

In class:

- Students are welcome to join the instructors in class to work on or discuss their final projects.

Week 11 Meeting 2 2022-12-05

In class:

- Students are welcome to join the instructors in class to work on or discuss their final projects.

Week 12 Meeting 1 2022-12-08

In class:

- Final project presentations by TBD.

Week 12 Meeting 2 2022-12-12

In class:

- Final project presentations by TBD.

Final project

This includes a written research proposal and in-class presentation.

Students will pick a transient of as-of-yet unknown origin (e.g., fast radio bursts, fast blue optical transients, extragalactic cosmic rays, high-energy neutrinos) or a gap in transient phase space and will write an observing/modeling/theoretical proposal for answering an interesting open question related to this. The students will present their proposals in class.