Advancing Theoretical Astrophysics
July 2019
Near Final Curriculum Outline

Mon 15 July

9:30-10:00: Welcome! Introductions, etc.

10:00-11:00: Intro to Order of Magnitude; OoMs for Compact Objects (Enrico + Sera)

Short description: OM magnitude problems. What determines the structure of compact objects. Calculate the binding energy density stored in BHs, NSs and WDs (stellar). Binding energy inventory of the Universe (a la Peebles). Need to talk about energy scales
Learning Objectives: What determines the structure of white dwarfs, neutron stars and black holes
Pre-requisites: undergrad physics

11:30-12:15 Inventory of Compact Objects in the Universe (Enrico)

Short description: Derive the energy density of black holes, neutron stars and white dwarfs

Learning Objectives: understanding the energy inventory of compact objects
Pre-requisites: undergraduate physics
Main teacher/lecturer: Enrico

12:15-13:00: Conservation Laws Using Stars (Andrew)

Short description: Conservation laws using stars
Learning Objectives: Given M/R of star, what's its central temperature? dP/dR ~ P/R. M/R of star if you fix T in central from H burning. Analytical derivation of the H-R diagram
Pre-requisites: undergraduate physics

14:45-16:45: Intro to Data Visualization (Daniela)

Short Description: This unit introduces learners to core themes of data visualization: How can we convey information using graphics? How does the human brain perceive shapes, colour, and space? How can we design effective visualizations that convey the information we want the reader to understand?

Learning Objectives: at the end of this unit, learners should have a basic understanding of perception and the role of pre-attentive processing to understanding visuals; they should be able to read a visualization and write down the key points conveyed by it; they should have co-created a set of best practices based on their observations; they should have worked in groups to constructively critique visualizations and prototype an alternative version of a visualization using paper and crayons. They should also have a working knowledge of best practices for working in teams.
Pre-requisites: None

17:15-18:30: Networking, upmentoring, and building your support systems, Community building

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Tues 16 July

9:30-10:15: Gaia H-R Diagram (Enrico/Daniela)

Short description: Derive H-R diagram with Gaia and show how it compares with the analytical formalism derived by Andrew in is class
Learning Objectives: Understanding of the H-R diagram
Pre-requisites: undergraduate physics

10:15-11:00: Astrophysical Timescales (Nicole)

Short Description: Relevant timescales in astrophysical scenarios
Learning Objectives: Student should be able to estimate the timescales relevant to various physical problems - e.g. dynamical timescales, hydrodynamic timescales, particle acceleration timescales, radiation/cooling timescales, diffusion timescales, etc.
Pre-requisites: Undergraduate physics

11:30-12:15: Short primer on fluid mechanics (Smadar)

Short description: Euler Vs Lagrange view, derivation of the continuity equation. Present the momentum equation if there is time.
Learning Objectives: Which forces act on a fluid? how can we describe fluid motion? learning the different views of Euler and Lagrange picture, and what are the advantages, derive the continuity equation from first principles. Present the momentum equation if there is time.
Pre-requisites: Undergraduate physics (know what are surface integrals and full derivatives)

12:15-1:30pm: More interactive fluid mechanics (Smadar/Sebastian)

Short description: focused on hydrostatic equilibrium, derive some useful scaling. Possible problems can be found here:

https://docs.google.com/document/d/1YhEby6S3VPl5x4YJRfa_pIueQdPPPwp-MaBKxZY7SoA/edit?usp=sharing
Learning Objectives: Some fun with fluids, focused on hydrostatic equilibrium
Pre-requisites: Undergraduate physics (know what are surface integrals and full derivatives)

14:45-16:45: Radiative processes I, Bremsstrahlung & Synchrotron (Sera)

Short description: Teach the (very) basics of radiation (accelerating charges) and a more OoM/qualitative treatment of bremsstrahlung and synchrotron, leading up to the actual formulae as well as info about where full derivations can be found.
Learning Objectives: Students understand that most HEA astrophysical processes are observed because of transverse waves from accelerating/decelerating charges, and can use the formulae to analyze source (will use Sgr A* as example).
Pre-requisites: Electromagnetism/electrodynamics, special relativity

17:15-18:45: Diversity Session with Visceral Change

Wed 17 July

9:30-10:15: How an Accretion Disk Forms (OoM) (Andrew)

Short description: How to form an Accretion disk
Learning Objectives: OoM thinking. Start with fixed mass (BH) and orbiting star. Centrifugal + gravity means stuff comes off, Roche Lobe, how accretion disk forms: energy loss (self-interacts & shocks) → circularize. Spreads out into disk.
Pre-requisites: undergraduate physics

10:15-12:15: Steady State Blackbody Circular Disk Problem (Andrew)

Short description: Set up and solve steady state black body circular disk
Learning Objectives: Set up and solve steady state black body circular disk
Pre-requisites: undergraduate physics

12:15-13:00: Astrophysical Shocks and Particle Acceleration (Irene)

Short description: OoM shocks and particle acceleration
Learning Objectives: Shocks, general principles of particle acceleration, Fermi acceleration, expected energy distribution of particles
Pre-requisites: Undergraduate physics

14:45-16:45: Radiative Processes II, Inverse Compton (Sebastian)

Short Description: Explore the fundamentals of inverse Compton scattering through brief discussion and hands-on tutorial
Learning Objectives: Understand MC modeling; understand the basic principles of inverse Compton scattering; understand the application and occurrence of IC in astrophysics
Pre-requisites: Basics of special relativity (Lorentz transforms)

17:15-18:45: Version control with git (Daniela)

Short Description: introduce the concept of version control, git, GitHub, adding and committing changes, understanding changelogs, publishing code on GitHub; potential add-on: pull requests and code review, giving constructive feedback
Learning Objectives: at the end of this unit, learners should be able to initialize a git repository, add and commit files, write descriptive commit messages, be able to review the changelog, and push changes to GitHub; after the add-on session, students should be able to understand how to open a pull request on someone else's repository, and how to give constructive feedback on someone's pull request;
Pre-requisites: Basic knowledge of the Unix shell (e.g. moving around directories, creating files/directories, working in a text editor)

Thurs 18 July

09:30-10:15: Jet power and acceleration (part I) (Sasha)

Short Description: Review the results of numerical simulations that show how accreting black holes form relativistic jets and, if there is time (of which there will not be), how jets accelerate.
Learning Objectives: At the end of this unit, the learners should be able to derive the expression for jet power from a spinning magnetized sphere and determine the maximum magnetic flux an accretion disk can hold on the black hole.
Pre-requisites: basic fluid dynamics, E&M
Main teacher/lecturer: Sasha

10:15-11:00: Jet power and acceleration (part II) (Oliver)

Short Description: introduce the 'acceleration by collimation' paradigm of relativistic jet dynamics. Discuss conservation laws, critical points and jet causality. Introduce basic scaling laws and discuss the accelerating field geometry.

Learning Objectives: at the end of this unit, learners should be able to use asymptotic relations to estimate the energy content of a jet and understand how fluid dynamical concepts apply to jet dynamics.
Pre-requisites: basic fluid dynamics, E&M

11:30-13:00: Diversity Session with Visceral Change

14:45-16:45: Compiling, running HARMPI, and visualizing the results (Sasha)

Short Description: show how to download, compile, and run the HARMPI code for a simple accretion problem, and visualize the results
Learning Objectives: at the end of this unit, the learners should be able to download, compile, and run HARMPI code. They should also be able to choose among several preset simulation setups. Using python (plus modules), they should be able to make plots of
Pre-requisites: Unix shell, python

17:15-18:45: Setting up problems in HARMPI (Sasha)

Short description: Setting up problems with HARMPI

Learning Objectives: Running Bondi-Hoyle, etc problems that were not already pre-set inside the code; Learning HARM
Pre-requisites: undergraduate fluid dynamics, E&M. general relativity (specifically raising/lowering of indices) is useful but not required.

18:30 - : How to Write an Effective Paper

Frid 19 July

9:30am-10:15: Orbits and motion in gravitational potential (Smadar)

Short description: Orbits in spherical potential, Kepler 2nd law is actually an angular conservation law, the different orbits (effective potential approach). ~45m
Learning Objectives: Spherical gravitational potential is common in astronomy. Learners will derive basic concepts associated with the relevant orbits.
Pre-requisites: Newton laws

10:15-11:am: Special case of orbits: The Hill/tidal/Lagrange L1 point (Smadar)

Short description: Presentation about Lagrange points. Then we will give the Hill/tidal/Lagrange L1 point, is given as an in-class problem, for the student to solve.
Learning Objectives: understand that the Hill/tidal/Lagrange L1 point all describe the same physics.
Pre-requisites: Newton laws

11:30am-12:15pm: Orbits work on problem (Smadar)

Short description: work on the problem of the Hill/tidal/Lagrange L1 point, is given as an in-class problem, for the student to solve. For the fast ones, there will be a bonus question about the tidal disruption event.
Learning Objectives: understand that the Hill/tidal/Lagrange L1 point all describe the same physics.
Pre-requisites: Newton laws

12:15pm-13:00pm: Classical Accretion Solutions - Bondi and Bondi-Hoyle-Littleton (Oliver)

Short description: Understanding Classical Accretion Solutions
Learning Objectives: Know your way around low angular momentum flows, intro to hydro, basic estimates (Bondi radius) and preparation for the computational curriculum.
Pre-requisites: ODE's

14:45-16:45: Low Angular Momentum Accretion (work problem; Sasha + Oliver)

Short description: Understanding accretion under low angular momentum conditions
Learning Objectives: Play around with GRMHD simulations and be creative. There are several things that can be done:

1. Verify the code using the Bondi solution found in the nonlinear ODE session.
2. Trigger the SASI instability for shock solutions.
3. Initialize a Bondi-Hoyle-Lyttleton accretion onto a (rotating) black hole, formation of a spiral shock and Flipflop instability. Connects to the Bondi-session.
4. Simulation of a black hole impacting on a disk (axisymmetric). Two shock bubbles are driven into the ambient medium, theorize on the radiative signature (binary black hole systems).

Pre-requisites: The HARM Tutorial

17.15-18.45: High-Energy Neutrino Astronomy and Astrophysics (Irene)

Short description: Neutrino production and propagation in cosmic accelerators.
Learning Objectives: Main processes leading to the production of high-energy neutrinos in cosmic accelerators. Connection to radiative processes. Observable effects.
Pre-requisites: Undergraduate physics

Sat 20 July

10:00: Diversity Session with Visceral Change

Continuation of HARMPI problems

Mon 22 July

9:30-11:00: Introduction to Bayesian Statistics (Daniela)

Core Themes: Probability and probability distributions, Bayes' theorem, priors, likelihoods, posteriors, designing a statistical model to match your problem;
Learning Objectives: at the end of this unit, learners should have a basic understanding of Bayes' theorem and how it fits in with their research work; they should be able to articulate the differences between prior, likelihood and posterior; they should be able to analytically calculate the posterior distribution for a particular problem; they will probably also have eaten a lot of M&Ms
Pre-requisites: learners should ideally have a basic understanding of probabilities and probability distributions (Chapters 12.1, 12.2, 13.1, 13.2, 18.1, 18.5 of this free textbook); they should have some very basic understanding of Jupyter notebooks and Python (see also this tutorial or this tutorial)

11:30-13:00: Nonlinear differential equations with singular surfaces: the wind equation (Chiara)

Core Themes: Introduction to the wind equation (Parker, Weber & Davis and general form) and methods to solve it. The problem of unknown location of the singularities. The importance of integrating away from the singularity. Combining root finding methods with minimization algorithms. Intro to Multinest.
Learning Objectives: The students will integrate the test equation in the classical way (towards the singularity) and compare the result with the integration away from the singularity. They will learn the basis of nested sampling and how to use Multinest for a specific problem.They will produce plots at each step of the algorithm to follow the progress and finally to present the solution.
Pre-requisites: some knowledge of Python and Fortran, like writing functions, defining variables, plotting.

14:45-16:45: Multinest tutorial (and relativistic Bondi accretion?) (Chiara)

Short description: We will use Multinest as the last step of the solution of the wind equation.

Learning Objectives: Students will understand the basis of the Multinest algorithm and run the code themselves and produce plots to visualize the minimization process and results.
Pre-requisites: some knowledge of Python and Fortran, like writing functions, defining variables, plotting.

16:30-17:45: Analyze/plot/visualize results of weekend HARM projects (Jason)

Short description: We will make plots and movies to understand simulation results
Learning Objectives: Students will be able to understand how to analyze numerical simulation results in terms of averaged 1D and 2D (time-dependent) quantities in terms of the saved dump files.
Pre-requisites: Familiarity with HARMPI code and variables and physical problem that was run

16:30-17:45: Analyze/plot/visualize results of weekend HARM projects (Jason)

Short description: We will make plots and movies to understand simulation results
Learning Objectives: Students will be able to understand how to analyze numerical simulation results in terms of averaged 1D and 2D (time-dependent) quantities in terms of the saved dump files.
Pre-requisites: Familiarity with HARM code and variables and physical problem that was run

18:45: Workshop with Dra. Nicole Cabrera

Tues 23 July

9:30-10:15: Introduction to Plasma Parameters (Nicole)

Short Description: Estimating and Understanding plasma and fluid parameters
Learning Objectives: Students will be introduced to fundamental plasma frequencies and length scales. They will be able to estimate plasma parameters in a given set up and be given examples of astrophysical applications in the context of collisionless shocks and, if time, reconnection. If time, they will also be able to estimate various MHD fluid parameters. They will be able to determine the degree of collisionality of a given set up and when to apply kinetic vs. fluid approximations to their problem.
Pre-requisites: Undergraduate physics

10:15-11:00: MHD Turbulence, Viscosity, Vorticity (Blakesley)

Short description: OoMs of Turbulence
Learning Objectives: Understand turbulent cascade and turbulent transport, Reynolds number, power spectrum, spectral scaling in the inertial range, handling turbulent data cubes
Pre-requisites: undergrad physics and fluid equation core theme above (momentum eqn.)

11:30-13:00: MHD Turbulence, Viscosity, Vorticity (Blakesley)

Short description: Magnetic fields and MHD
Learning Objectives: Topics in basic MHD and MHD turbulence. Understand the physics behind flux freezing, basics of MHD waves
Pre-requisites: undergrad physics and fluid equation core theme above (momentum eqn.)

14:45-16:30: Workshop with Dra. Nicole Cabrera

16:30-19:30: How to Give a good talk with Karen Harrebout

Wed 24 July

9:30-12:15: Intro to Machine Learning, pt. 1+2 (Camille)

Short description: Prediction versus inference; supervised versus unsupervised machine learning; linear models, k-nearest neighbour (maybe k-means); cross-validation and scoring; practical machine learning. Possible add-on: intro to neural networks, how machine learning fails in the real world (and the consequences)
Learning Objectives: by the end of the unit, learners should have a sense of where and when machine learning is useful and be able to distinguish supervised from unsupervised learning methods. They should understand how simple machine learning algorithms like k-nearest neighbour and k-means operate, and know the difference between training, validation and test sets. They should be able to execute simple machine learning algorithms using scikit-learn and be able to explore the results. After the add-on, learners should have a basic understanding of neural networks, and have an idea of when and where machine learning is used in science and beyond, and where and how these algorithms fail
Pre-requisites: learners should ideally have some basic familiarity with programming in Python, at the level of defining variables, writing for-loops, and doing some basic plotting.

14:45-16:45: Disk-Jet Connection (Jane + Sasha)

Short description: Overview of how accretion and jets are connected
Learning Objectives: Overview of how accretion and jets are connected
Pre-requisites: undergraduate physics

17:15-18:45: GR Ray Tracing; Runge-Kutta (Jane)

Short description: Ray-tracing around black holes

Learning Objectives: A combination of astrophysics and scientific computation. GR metric around black holes and geodesics. Ray-tracing basics. Introduction to using the Runge-Kutta method to solve PDEs numerically. Supply the students with a partially finished code of the geodesic equation of motion using the Runge-Kutta method and ask them to finish the rest. At the end of the class, the students can plot the trajectory of a single particle or a photon ray around a spinning black hole.
Pre-requisites: some basics of C/C++ and linux

18:45-19:15: HARM study of Low luminosity accretion, radiation processes

Short description: We will analyze HARM results for low-luminosity accretion by scaling GRMHD simulations to match source properties of Sgr A* and/or M87, make estimates and calculations of what radiative processes should be most relevant, and make predicted spectra and resolved black hole images/movies (e.g. for comparison with the EHT image of M87)
Learning Objectives: Students should understand how observables can be calculated from GRMHD simulations of black hole accretion for a particular source
Pre-requisites: Familiarity with HARMPI code, low-luminosity accretion, radiative processes and radiative transfer, and geodesics/ray tracing

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Thurs 24 July

9:30-11:00: Derive M-sigma (Andrew)

Short Description: Deriving the relationship between stellar velocity dispersion and mass of the central black hole in a galaxy.
Learning Objectives: OoM thinking. Do Eddington limit first (they do). Start with isothermal distribution of stuff (Kepler) around central mass, total mass enclosed linear in radius, T=vel. Dispersion. Blow on this with Eddington momentum because wind cools, what’s the limiting mass? Turns out to be M-sigma!
Pre-requisites: undergraduate physics

12:15-13:00: Introduction to the Einstein Toolkit (Sasha)

Short Description: Introduction to Einstein Toolkit, guiding principles, community, resources; show how to download, compile, and run the code; show gallery examples and showcases
Learning Objectives: at the end of this unit, the learners should know what the Einstein Toolkit is and how it can be used. They should also know where to download the code and find documentation for getting started using the Einstein Toolkit for their own research.

14:45-15:30 Multiwavelength SED fitting with Isis (Sera)

Short description: Most high energy astrophysical objects radiate from radio through gamma-rays, so it is important to be able to fit data from across the entire SED. This turns out to be quite challenging if you want to do this statistically, since ideally you want to forward fold your model to compare with data

in detector space for X-ray and gamma-ray data, while for radio/IR/optical you can fit directly to fluxes. There is no ideal program for this yet but one that can handle most codes is Isis, I will give an example (something like a guided tutorial) of how to use it for a custom model.
Learning Objectives: Learn what is involved in fitting MWL data, learn enough basics of Isis to be able to use in future if interested.
Pre-requisites: None
Main teacher/lecturer: Sera

Fri 25 July

9:30-11:00: OoM Blast Waves (Enrico)

Short description: An order of magnitude approach to Blastwaves (Impulsive solutions), SN lightcurves and Remnants; Wind driven expansion
Learning Objectives: Understanding energy scales, timescales and general observables; What determines the evolution of blastwaves , radioactive powered transients and supernova remnants. Understanding momentum and energy deposition.
Pre-requisites: undergraduate physics