Draft curriculum map

Student Learning Outcomes

1. Laws of Physics - Explain the physical laws and concepts of classical mechanics, thermodynamics and statistical mechanics, electromagnetism, optics, relativity, and quantum mechanics.
2. Astronomical Objects - Describe the nature, structure, distribution, and formation of astronomical objects, including planets, stars, and galaxies, and the history of the universe.
3. Physical laws in Astronomy - Demonstrate an appreciation of the universality of physical laws and apply these laws to explain phenomena in astronomical systems and the universe
4. Astrophysical Problems - Formulate astrophysical problems in mathematical terms and use analytic and numerical methods to obtain solutions
5. Scientific Method - Use the scientific method to ask meaningful questions, to design experiments to address these questions, to acquire and critically analyze the data, and to draw appropriate conclusions.
6. Scientific Communications - Communicate research design and results effectively in both written and oral formats.
7. Observational Properties - Define and interpret the observational properties of astronomical objects
8. Astronomical data reduction - Reduce astronomical images and spectra using standard analysis software, and measure observational properties from reduced data.
9. Observing methods - Propose, plan, and conduct astronomical observations with professional telescopes
10. Astronomical literature - Use sources from astronomical literature, databases, and on-line catalogs to obtain relevant information about astronomical objects and theories.

Notes

1. Laws of Physics -

Explain the physical laws and concepts of classical mechanics, thermodynamics and statistical mechanics, electromagnetism, optics, relativity, and quantum mechanics.

contents

Subject	Introduction	Basic Usage	Mastery
Classical mechanics (forces)	1D, constant forces applied using Newton's laws; use of free-body diagrams	2D & 3D; pressure as force / area	time and position varying forces, use of differential equations
Classical mechanics (energy)	Apply conservation of energy to examine events in 1D (e.g. collisions)	Minimization techniques	Use Lagrangian to examine dynamics of a physical system
Classical mechanics (momentum)	Conservation of momentum in 1D motion, connections with force and energy at this level	Collisions in 2D and 3D; model impulse as force x time	
classical gravity	qualitatively identify gravitational influences; calculate static effect	circular orbits, tidal effects	elliptical orbits, continuous mass distributions
Electrostatics	force 1/r2 relation and calculation of electric potential for point charges	continuous distributions, dipoles	quadrupoles
Electromagnetism	Interaction between changing electric and magnetic fields	polarization	radiation from
Light as a wave	basic wave properties	wavefront model of refraction, derivation of snell's law, 1D diffraction	
Light as a particle	Photon energy hnu, qualitative description of photoelectric effect	stopping function	
Geometrical Optics	Ray model of light, thin lens equation	Use of ray diagrams to interpret and design optical systems (e.g. magnification, inversion)	Fourier & gaussian optics Optical Design Aberration theory
Gaussian Beam Optics	Definition, Propagation equations	Derivation from E+M	
Physical/Fourier Optics	Basic QED, diffraction	Fresnel, Fraunhofer diffraction	
Quantum mechanics	Energy levels of particle in a 1D box; tunneling	Electronic energy levels of Hydrogen atom, ionization of hydrogen atom	Energy levels of perturbed potentials, Tunneling to overcome nuclear potential
Thermodynamics	temperature as representation of mean molecular kinetic energy	Adiabatic systems, work done by a system	Open systems, state changes
Statistical mechanics	Equation of state, distribution of velocities / energies / etc.	Blackbody radiation	Degeneracy in quantum systems
Special relativity	Introduce idea that speed of light is the same in all frames, constant motion, space-time diagrams	Derive consequences of speed of light the same in all frames	

Fluid dynamics?			
Solid-state physics?			
General relativity?			

2. Astronomical Objects -

Describe the nature, structure, distribution, and formation of astronomical objects, including planets, stars, and galaxies, and the history of the universe.

contents

Subject	Introduction	Basic Usage	Mastery
Stars	Properties: mass, luminosity, temperature; calculations based on tabulated temperature and luminosity (relative lifetimes, radii); use HR diagrams to determine relative ages of groups of stars	Processes: Jeans collapse, fusion → luminosity; stages of fusion; 1D structure; post-main sequence evolution	2D & 3D structure; IMF and interpretation of stellar populations as sum of multiple populations over time
The Sun	Properties and use as a benchmark	Processes: core fusion and neutrino production, sunspots and magnetic field production,	
Stellar remnants	Properties of brown and white dwarfs, neutron stars, black holes	basic degeneracy calculations	
ISM	Properties: ISM, atomic clouds, 2-phase, molecular clouds, HII regions, planetary nebulae, SN remnants, hot ionized medium, 3-phase, star formation, feedback [JPW]	basic estimates and interpretation of line absorption and emission, reddening, shock structures	
Circumstellar disks	Properties: size, mass, keplerian rotation, conservation of angular momentum, gas, dust (grain growth), snowlines [JPW]	derive continuum emission for simplified case (e.g., flat black disk); interpret basic image and velocity map data	model line emission given a density and temperature structure; iterative radiative transfer to estimate structure
Worlds, rocky	Properties (I would split these up - rocky and icy are quite different) [JPW, KJM]	simple cooling curve	
worlds, icy	properties	simple tidal heating examination	
Worlds, gaseous	Properties		
Asteroids & Comets [RJ]	Properties: basic formation, morphology, composition, location and size distribution [RJ]	orbit evolution, collisional evolution, Yarkovsky, YORP [RJ]	Nice Model, Grand Tack Model, other models, multiple systems, thermal history, dating, rotational properties [RJ, KJM]
Galaxies	Structure of spiral and elliptical galaxies Star-gas-star cycle (RRG)	Evolution, formation, interactions (RRG)	Feedback, galaxy-cluster interactions, quenching & triggering (RRG)
Active galactic nuclei	Supermassive BH + gas (NJM)	Radiation from accretion disk, interaction of radiation with surrounding matter (NJM)	Radiative transfer and models of components (accretion disk, dust, clumpy gas vs. smooth ISM, viewing angle, inflows + outflows) to

		Eddington limit (NJM)	explain variety of observed AGN properties (NJM)
Galaxy clusters	Cosmic web; constituents - DM, gas, galaxies (RRG)	Differential galaxy evolution Xray L/T, velocity dispersion, mass measurement (RRG)	lensing, SZ effect, ISW (RRG)
Dark matter	Discovery and measurement of dark matter via rotation curves	Gravitational lensing	Dark matter dynamics
The Cosmos	Discovery of Hubble law and measurement of expansion timescale	Calculation of expansion timescale and discovery of acceleration; qualitative description of universe components	
Subject	**Introduction**	**Basic Usage**	**Mastery**
Habitable Worlds	Characteristics of habitability: physical & orbital properties of body, requirements for life [KJM]	concept of habitable zone, quantitative exploration of HZ in different star systems [KJM]	HZ evolution in time, galactic HZ [KJM]

3. Physical laws in Astronomy -

Demonstrate an appreciation of the universality of physical laws and apply these laws to explain phenomena in astronomical systems and the universe

contents

Subject	**Introduction**	**Basic Usage**	**Mastery**
Orbital motion	Kepler's Laws. Newton's version of Kepler's 3rd law. Circular orbits with a negligible mass.	General 2-body problem. Perturbations; secular evolution.	Non-Keplerian potentials; orbital invariants
Continuum mechanics	Hydrostatic equilibrium: atmospheres.	Hydrostatic equilibrium: planetary & stellar interiors.	Solar & stellar winds; time-dependent problems; shocks.
Matter & Radiation	Stefan-Boltzmann & Wien's laws. Qualitative description of Interaction of light & matter	Planck function and Rayleigh-Jeans approximation; hydrogen levels; line formation in LTE.	Non-LTE systems; astrophysical masers.
Nuclear Reactions	alpha and beta decay. Fusion and fission	Hydrogen and helium burning. CNO cycle vs PP	Reaction networks; R and S process.
Chemistry	Temperature and pressure conditions for molecular stability	Conditions for formation	Molecules as probes of physical conditions
Mechanics (RRG)	Newtons laws (RRG) Conservation laws (RRG)		
Energy	Classifying energy reservoirs and transformation mechanisms in a system	Comparing rates of energy transfer to ID dominant mechanisms	
Degenerate systems	Extremes leading to degeneracy (i.e., the clear-cut cases)		
Behavior of light	straightline motion; first step in measuring sizes and distances	finite speed; polarization	following deformations of space: cosmological redshift and lensing
Quantum nature of matter	Bohr atom (with conservation of energy and angular momentum)		

4. Astrophysical Problems -

Formulate astrophysical problems in mathematical terms and use analytic and numerical methods to obtain solutions

contents

Subject	Introduction	Basic Usage	Mastery
Represent physical situation in mathematical terms	verbal and schematic descriptions	match descriptions to known functions	construct formulae, derivatives, integrals, etc.
Algebra	Map physical situation to known functions, plug in values to a function and solve for unknown	Symbolic manipulation: reformulate functions to examine situations from other angle (i.e. solve equation to represent arbitrary independent / dependent variables); Proportional reasoning	Combine multiple functions with variables in common to explore relations between previously unrelated variables
Numerical modeling	Setup basic “stocks-and-flows” models	Create multi-object models	
Graphical representations	scatter plot, histogram, and cumulative distributions		
Statistical descriptions	mean, median, mode, standard deviation, and error on the mean	meaning of the above (mean, etc.) in context of generalized probability distributions (NJM)	
Statistical tests	correlation coefficient; binary tests (e.g. Fisher exact test)	K-S test	
1D calculus	construct derivative or integration statement from situation		
Multivariate calculus		Change of axes (e.g., dxdy → rdrdθ) for convenient problem solving	
Differential equations	Qualitatively describe behavior of systems model-able with positive and negative feedback	solve systems of linear differential equations	
Trigonometry	size of Earth; parallax; linear size determination		
Spherical geometry	coordinate systems		
Analytical parameter estimation	linear fits		
Numerical parameter estimation	basic grids and use of chi-sq values to estimate best-fit parameters		
Bayesian methods	ID reasonable priors, construct statement, and calculate posterior		
Linear algebra			
Monte Carlo methods? [JPW]			

5. Scientific Method -

Use the scientific method to ask meaningful questions, to design experiments to address these questions, to acquire and critically analyze the data, and to draw appropriate conclusions.

contents

Subject	Introduction	Basic Usage	Mastery
Develop answerable questions	Ask questions	Classify as observation (how many, what shape) vs. mechanism (why, what happens if...) questions	Identify further consistent and/or inconsistent observations Revise broad questions into testable ones (NJM)
Identify correlated or independent / dependent variables	By measurement, determine whether two variables are correlated or uncorrelated (NJM)	Measurements to determine correlation between X and Y, while controlling for Z (NJM)	
Characterize patterns in data	Qualitative description of trends in data	Plotting and simple fitting (RRG)	Model fitting (RRG)
Identify underlying mechanisms for relations	Correlation vs. causation	ID pseudoscience	
Reductionism			
Drawing conclusions (RRG)	Statistical meaningfulness (qualitative understanding -RRG)	Applying appropriate statistics; quantifying uncertainty (RRG)	

6. Scientific Communications -

Communicate research design and results effectively in both written and oral formats.

contents

Subject	Introduction	Reinforcement	Mastery
Technical descriptions	Completely list or tabulate all information to recreate an observation or technique		Well organized description that is complete and reader friendly
Visual representation	How do images and plots convey information (RRG) (i.e. be able to read a scatter plot vs. histogram vs. cumulative distribution plot)	Using color, symbols to encode data; histograms and contour plots; choosing what is immportant and designing a figure (RRG)	Tailoring figures to the medium (paper vs. oral presentation)
Outline history of ideas	Trace discoveries back by date and discoverer	Identify key discoveries and connections between concepts	explain limitations of data or theory - why finding was “This” rather than “that”
Presentation of results	Clear presentation of raw data	Basic summaries of data (e.g. averages, standard deviations)	Presentations of data that ease analysis (well thought out emphasis)
Presentation of reasoning	Complete presentation of logic	Clear step-by-step presentation of logic, with effective asides and parentheticals	Well thought out presentation, with pedagogical tools as needed (e.g. series of figures illustrating build-up of a data-set or shifting emphasis among points)
Communicate importance of result	Identify how a result extends current knowledge	Identify new questions raised by a result	Identify broader implications of work
Parsimonious communication	identify key points leading to conclusion	Include only what leads from background to conclusion	work backwards from conclusion you are presenting
Grant Proposals	What, why and how of an investigation.	Group assesment of propsal abstracts	

7. Observational Properties -

Define and interpret the observational properties of astronomical objects

contents

Subject	Introduction	Reinforcement	Mastery
Brightness	flux, surface brightness; filters	Spectral Energy Distribution, colors	contrast ratio measurements
Luminosity and apparent brightness	Integrate SED	Bolometric correction	
Wavelength dependence	Atmospheric windows, resolution	emission regimes (e.g. in the Rayleigh-Jeans) and characterizing SEDs with power-laws	
Spatial distribution	Spatial density	two-point correlation functions	
Distance	Distance ladder; standard candles, parallax; redshift (RRG)	peculiar velocities, calibratable standard candles (like SN !a) (RRG)	More complex methods (tRGB, T-F, etc.); creating 3-D maps (RRG)
Position	Coordinate systems (RA/Dec, Galactic, Alt/Az), Precession	Astrometric measurement & accuracy of point sources, proper motion	Centroiding, crowding, blending, motion during obs
Morphology	Classification, visual vs. computational (RRG)	Quantititative morphological properties (asymmetry, ooncentration etc. - RRG)	Sersic index, model fitting
Spectroscopic details	EW, depth, integrated flux, wavelength → element or compound	data cubes, 0th & 1st moment maps, velocity profiles	line ratio maps and estimation of optical depths / excitation conditions
Time-dependent / series	qualitative fitting of simple functions (e.g. sine curve)	Fourier methods (RRG)	
Interferometry	uv-coverage and maximum / minimum scales, qualitative understanding of 1D real & imaginary profiles	quantitative mapping of features in 1D real & imaginary profiles to image plane	model fitting to 2D visibility data
Polarization			
PSF fitting	Achievable contrast vs. separation	PSF subtraction techniques	

8. Astronomical data reduction -

Reduce astronomical images and spectra using standard analysis software, and measure observational properties from reduced data.

contents

Subject	Introduction	Reinforcement	Mastery
Understand nature of different contributors to errors in data	Systematic vs. random errors, qualitative distributions, examine process, independent vs. correlated error	Classify sources of error in measurement and model accordingly (i.e. Poisson or Gaussian?). Approximate errors as gaussian. Use propagation of errors.	Use non-Gaussian error models. Use computational techniques to characterize errors (e.g. recovery of inserted objects to data). Account for correlated noise.
CCD image data reduction	Basic calibration and measurement (darks, flats, standards, aperture photometry)	Coadding, registering, astrometry (RRG)	Pipeline writing
Spectroscopy data reduction	Single order spectroscopy, calibration and measurement	coadding, binning	Cross-dispersed spectroscopy, Pipeline writing IFU spectroscopy
Compensate for systematics, foregrounds and backgrounds	Skylines, ISM dust, SMGs		
Finding the right tools	Existing manuals & pipelines, general purpose tools (e.g. AstroImageJ); coding languages (Python, IDL, etc - RRG)	ID deficiencies and limitations, combine or modify existing tools	roll-your-own
Measurement	Aperture photometry relative to standards	Conversion of flux ratios to magnitudes, measurement in various magnitude systems (e.g., Vega, Sloan)	
Making data meaningful and scientifically useful	converting to physical quantities	estimating random and systematic errors	Evaluating when measurements are applicable, given their systematics. E.g., can I compare my gas-phase metallicity measurement in a spiral to Dr. X's stellar metallicity in an elliptical? Perhaps this is more of a "scientific method" skill … (NJM)
Using facility tools	run prebuilt reduction scripts	install facility tools, modify standard scripts	

9. Observing methods -

Propose, plan, and conduct astronomical observations with professional telescopes

contents

Subject	Introduction	Reinforcement	Mastery
Proposal writing	Basic components: background , context, and literature search; clear statement of question, description of technique and choice of targets	Refine basics, improve presentation (esp. figures)	Compelling astronomical context, extend current knowledge
Observations that sufficiently address a scientific question	Sufficient number of observable targets	Comparison of proposed observations to theory	Fine tuning of numbers / targets / instrument
Trace light from source to detector (systematics)	Qualitatitve discussion of sources of systematics (RRG)	Quantitative measurement of effects; finding data on atmospheric/telescope/instrument transmission & QE (RRG)	Using data to self-characterize (RRG)
Telescope capabilities (how we observe different parts of spectrum)	resolution (spatial, temporal, spectral/energy), sensitivity, range	Statistics & noise characteristics, foregrounds & backgrounds, saturation and detectability	Confusion, detector limited, sky limited, more detailed S/N calcs
Interplay between scientific needs and telescope capabilities			Adjust scientific goals with capabilities in mind
From observations to data	outline steps	consider how errors will propagate	work backward to streamline process
carrying out observations	prepare ordered target list with standards, carry out pre/post observation calibrations, carry out observations	estimate quality of incoming observations and adjust integration times	estimate quality of incoming observations and weather conditions and adjust multiple aspects of strategy

10. Astronomical literature -

Use sources from astronomical literature, databases, and on-line catalogs to obtain relevant information about astronomical objects and theories.

contents

Subject	Introduction	Reinforcement	Mastery
Publication process	Overview of “the system” - refereed vs. public review vs. conference proceedings (invited vs. contributed)	Evaluation of pros / cons of “the system”	Write a paper, and review
Find and access relevant papers	Introduction to resources (journals, ADS, trace references, key words and topics, ARAA, conference proceedings, ArXiV, ScholarSpace, VoxCharta, online resources (Astrobetter, facebook groups))	write a literature review	Identify papers that should have been referenced by a publication
Access and evaluate data from papers	Identify systematic and random errors in reported data	Ingest data to your own usage scheme, converting units as needed	Ingest data from multiple sources, weighing them according to reliability
Access and evaluate figures from papers	Describe trends seen in figures	Relate trends to underlying physics, Make inferences regarding populations	
Access and evaluate data from data archives (e.g. Vizier, image servers)	Intro to services (Vizier, CDS, Skyserver - RRG)	SQL queries (RRG)	Telescope archives (RRG)
Put work in context	Identify the field this work contributes to and connections to other fields	Identify the type of contribution (e.g., improved statistics, identify a new mechanism, present a new analysis technique)	Identify new research questions based on the work
Critically evaluate methods and results in scientific publications	Examine assumptions, consistency check results with other works	Reproduce analysis and results using stated methods	Use results to re-evaluate other works
Efficiently read papers	Read through a paper, making noes and writing a summary afterwards	Read from overview to high-detail levels (e.g. abstract, conclusion, figures, techniques, results, discussion)	Read strategically, continuously evaluating when sufficient knowledge has been gained

Notes and references

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Approach to polishing this:

1. Pick one of these dimensions as the central organizing principle for their course. In most cases, instructors are likely to pick “2. Astronomical Objects”.
2. High level listing of topics, organized along that category. E.g., many course syllabi consist of a listing of astronomical objects studied.
3. Beneath each topic, identify course material relevant within the other categories. E.g., ASTR 110 coverage of the sun might include: 1) blackbody radiation, hotter → less dense, buoyancy, flowing charged particles → magnetic fields, magnetic fields trap charged particles, nuclear fusion; 3) fusion powers stars, hydrostatic equilibrium; 4) geometry to estimate sunspot sizes

2. Astronomical Objects -

Describe the nature, structure, distribution, and formation of astronomical objects, including planets, stars, and galaxies, and the history of the universe.

Subject	Introduction	Reinforcement	Mastery
Stars	Properties: mass, luminosity, temperature; calculate relative lifetimes and use HR diagrams to determine relative ages of groups of stars	Processes: Jeans collapse, fusion → luminosity; stages of fusion; 1D structure; post-main sequence evolution	2D & 3D structure; IMF and interpretation of stellar populations as sum of multiple populations over time

3. Physical laws in Astronomy

Subject	Introduction	Reinforcement	Mastery
Continuum mechanics	Hydrostatic equilibrium: atmospheres.	Hydrostatic equilibrium: planetary & stellar interiors.	Solar & stellar winds; time-dependent problems; shocks.
Nuclear Reactions	alpha and beta decay. Fusion and fission	Hydrogen and helium burning. CNO cycle vs PP	Reaction networks; R and S process.

4. Astrophysical Problems

Subject	Introduction	Reinforcement	Mastery
Numerical modeling	Setup basic “stocks-and-flows” models	Create multi-object models	

10. Astronomical literature

Subject	Introduction	Reinforcement	Mastery
Access and evaluate data from papers	Identify systematic and random errors in reported data	Ingest data to your own usage scheme, converting units as needed	Ingest data from multiple sources, weighing them according to reliability

Subject	Introduction	Basic Usage	Mastery
Orbital motion	Kepler's Laws. Newton's version of Kepler's 3rd law. Circular orbits with a negligible mass.	General 2-body problem. Perturbations; secular evolution.	Non-Keplerian potentials; orbital invariants

Subject	Orbital motion
Introduction	Kepler's Laws. Newton's version of Kepler's 3rd law. Circular orbits with a negligible mass.
Basic Usage	General 2-body problem. Perturbations; secular evolution.
Mastery	Non-Keplerian potentials; orbital invariants