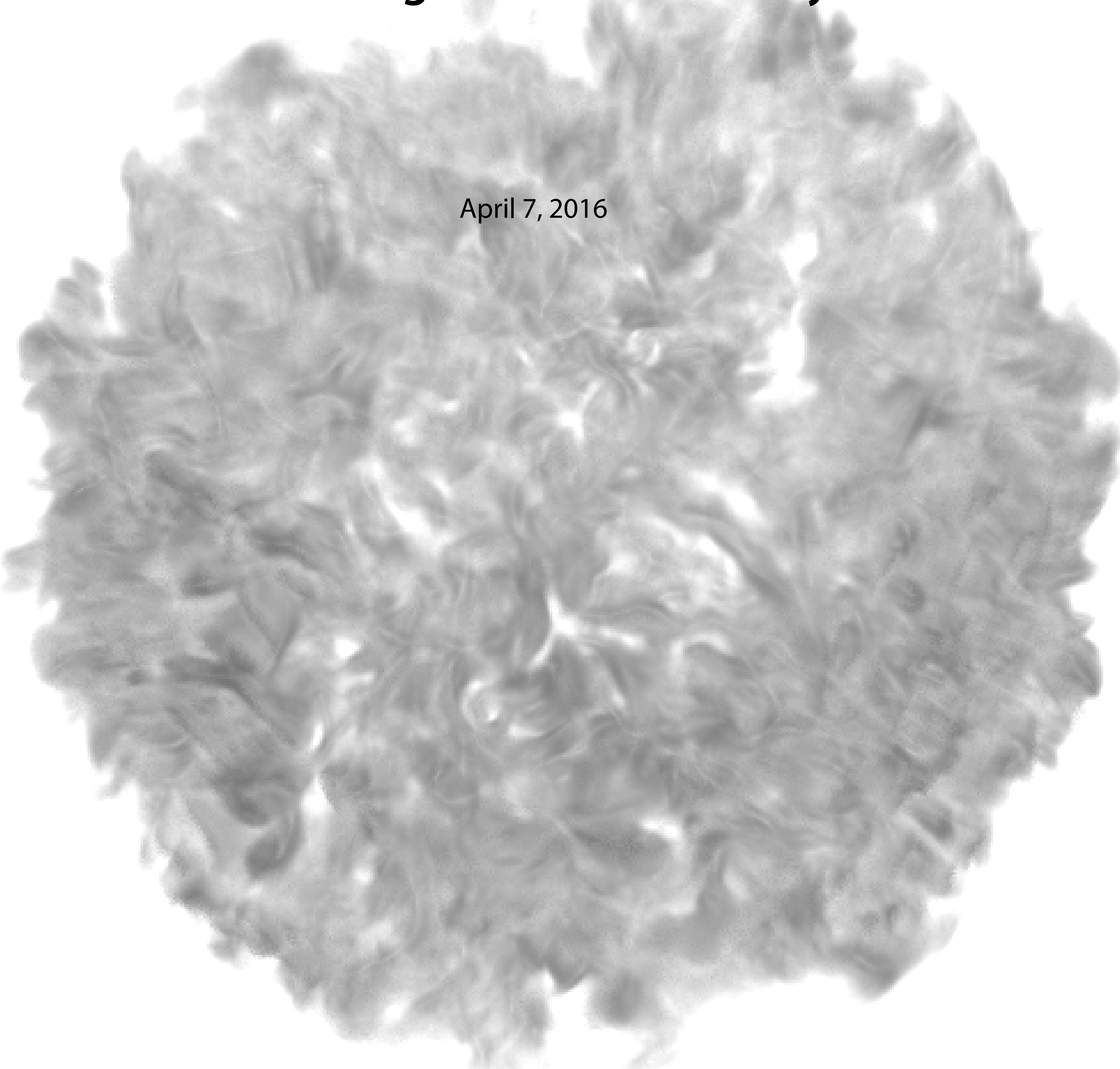
Training the Next Generation of Astronomers at Michigan State University



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Summary

We propose to restructure the course requirements for the Astronomy and Astrophysics Ph.D. program at Michigan State University. Our proposed changes increase the flexibility of our course structure and bring in courses on emergent topics, such as the statistical handling of large datasets and modern computational methods.

On the cover is a visualization from a simulation of a massive star just prior to collapse and explosion as a supernova. The simulation was performed with the FLASH code using input models constructed with the `MESA` code. Credit: S. Couch, MSU.

1 Adapting the Graduate Program in Astronomy and Astrophysics

Recognizing the rapid development of computation and its indispensable role across many scientific disciplines, Michigan State University has created a new department of Computational Mathematics, Science, and Engineering (CMSE). Currently two (out of nine) members of the astronomy group, Professors O'Shea and Couch, have joint appointments with CMSE. Two other members of the astronomy group, Professors Voit and Brown, have interests that also rely on computation. In the fall of 2016, Dr. Luke Roberts, a theoretical astrophysicist with interests in computational modeling, will join the nuclear theory group at the NSCL. The growing prominence of Michigan State in computational astrophysics is having an impact on our graduate recruiting. Indeed, of students currently being recruited, over half have expressed interest in computation, and several indicated that the new department motivated them to apply to Michigan State.

Observational astronomy is undergoing remarkable changes, driven both by advances in detectors, which allow a large field-of-view to be imaged, and by the huge leaps in computing power necessary to handle extraordinarily large datasets. The priorities of the astronomy community in the U.S., as described in the most recent astronomy decadal surveys[1] show that astronomy has entered the era of "big data". A key theme to emerge from the decadal surveys is the importance of large-scale surveys and the study of transient phenomena in the universe. The 2010 survey stated that the highest priority for the NSF in the upcoming decade should be the Large Synoptic Survey Telescope (LSST). The LSST is a large, 8.4 m, ground-based optical telescope that will be located on Cerro Pachón in Chile—the same site as MSU's own SOAR telescope. LSST's survey of astronomical objects will be unprecedented in breadth and scope. LSST is being preceded by a number of more targeted surveys, including Pan-STARRS, SDSS-3, and the Palomar Transient Factory in the northern hemisphere, and Skymapper and the Dark Energy Survey in the southern hemisphere.

In response to these new capabilities, astronomers are increasingly expected to adroitly manipulate large datasets and to work with sophisticated algorithms for asking questions of these datasets. The need to train theoretically-minded students in computational methods and observationally-minded students in statistical methods compels us to build more flexibility into the courses required for a degree in astronomy and astrophysics. Further, most students that receive PhD's work outside academia, and many of these careers heavily use computational modeling and data science[2]. Additional training in these subjects, and flexibility in this training to accommodate the diverse careers of physics and astronomy PhDs, will make the MSU astrophysics PhD program more desirable and competitive.

2 The Current Graduate Program

The current requirements for the Ph.D. in Astrophysics and Astronomy are specified in the *Handbook for Graduate Students* (16 August 2015 version). Astrophysics students currently complete the following required courses.

Physics courses: Classical Mechanics (PHY 820), Statistical Physics (PHY 831), Electricity and Magnetism I (PHY 841, Nuclear Astrophysics (PHY 983)

[1] The goal of these decadal surveys, which are commissioned by the NSF, NASA, and the DOE, is to identify the most pressing science questions and highest priority facilities for the next decade. The most recent survey was just completed, with the results published in the book *New Worlds, New Horizons* (available from the National Academy Press). This survey was aimed at initiatives that will begin in the decade 2010–2020.

[2] See Czjuko and Anderson, *Common Careers of Physicists in the Private Sector,* 2015, AIP (`https://www.aip.org/statistics/reports/common-careers-physicists-private-sector`).

Astronomy courses: Radiative Processes (AST 810), Galactic Astronomy (AST 825), Extragalactic Astronomy (AST 835), Stellar Physics (AST 840)

Astrophysics students must pass the core physics or their subject exams and the core astronomy courses with a grade of 3.375, averaged over all core courses. In addition, astrophysics students must complete the two-semester AST 805 research project at the Ph.D. level. The oral examination at the completion of the project serves as the student's comprehensive examination.

3 The Proposed Graduate Program

We propose to replace the eight specific required courses listed above with the requirement that the student take in total eight courses comprising the four astronomy courses (AST 810, AST 825, AST 835, and AST 840), two of the physics subject exam courses (PHY820, PHY 831, PHY 841, and PHY 851), and then two additional courses (6 credits) selected from the core physics, astrophysics, or computational courses (see Appendix A). Students would be required to meet with the astronomy graduate advisor at the start of every semester to discuss their coursework, in consultation with the research advisor for the second year project.

Astrophysics students would be required to pass this set of 8 courses, or their subject exams when applicable, with an average grade of 3.375, the same as the current requirement. Also unchanged from the current program is the requirement that astrophysics students must complete the two-semester AST 805 research project at the Ph.D. level. The oral examination at the completion of the project will continue to serve as the student's comprehensive examination. The requirements for the qualifying exam and the formation of a guidance committee would remain unchanged.

In addition, we propose to expand AST 911 to a 3 credit course and change its title from "Numerical Techniques in Astronomy" to "Numerical and Statistical Techniques in Astronomy." Note that this course will be accepted for the CMSE graduate certificates and degrees, and we therefore propose that it be cross-listed as a CMSE course.

A Core Courses

Course descriptions are as listed by the registrar, with the exception of AST 911 and AST 912, for which we give revised descriptions.

A.1 Astronomy & Astrophysics

AST 810 Radiation Astrophysics— Transfer of radiation through plasmas and processes for emission and absorption of photons. Interpretation of the spectra of stars, the interstellar medium, and galaxies.

AST 825 Galactic Astronomy— The Milky Way as a galaxy. Observations and techniques of theoretical analysis that are used to discover the features of our galaxy.

AST 835 Extragalactic Astronomy— Galaxies beyond the Milky Way. Large-scale structure of the universe. Cosmology.

AST 840 Stellar Astrophysics— Physics of stellar interiors. Methods for calculating stellar models. Principles of stellar evolution.

AST 911 Numerical and Statistical Techniques in Astronomy— Fundamental numerical methods with application to astronomy and astrophysics. Methods for extraction of information from large datasets.

AST 912 Observational Astronomy— Fundamentals of observational astronomy. Aspects of telescope and instrument design, astronomical observations over a range of wavelengths, and data analysis techniques.

A.2 Physics

PHY 810 Methods of Theoretical Physics— Theoretical methods used in classical mechanics, quantum mechanics, electrodynamics, and statistical mechanics.

PHY 820 Classical Mechanics— Two-body central force problem, Hamilton's principle, Lagrangian and Hamiltonian equations of motion, variational methods, small oscillations, classical fields.

PHY 831 Statistical Mechanics— Equilibrium statistical mechanics and thermodynamics. Boltzmann transport equations and hydrodynamics. Brownian and Langevin motion.

PHY 841 Classical Electrodynamics I— Electrostatics, magnetostatics, time-varying fields and Maxwell's equations. Gauge transformations. Poynting's theorem and conservation laws.

PHY 842 Classical Electrodynamics II— Plane electromagnetic waves, polarization states, reflection, refraction. Wave guides and resonant cavities. Radiating systems, dipole fields, radiated power. Special theory of relativity.

PHY 851 Quantum Mechanics I— Axioms of quantum and wave mechanics, applications to spherically symmetric potentials. Hydrogen atom, harmonic oscillator, matrix mechanics, angular momentum theory, rotations.

PHY 852 Quantum Mechanics II— Approximation methods, perturbation theory, atomic physics applications, scattering theory, identical particles, Pauli principle, Bose and Einstein statistics, Hartree-Fock approximation, collisions of identical particles, radiation.

PHY 983 Nuclear Astrophysics— Low energy reaction theory, survey of astrophysics, physics of nuclei and reaction relevant to astrophysics, nuclear reaction rates in stellar environments, stellar evolution, solar neutrinos, big bang nucleosynthesis, dark matter, supernova explosions, r-process, hot CNO and rp-process, cosmochronology.

A.3 Statistical & Computational

CMSE 820 Mathematical Foundations of Data Science— Fundamental mathematical principles of data science that underlie the algorithms, processes, and methods of data-centric thinking, and tools based on these principles.

CMSE 821 Numerical Methods for Differential Equations— Numerical solution of ordinary and partial differential equations, including hyperbolic, parabolic, and elliptic equations. Explicit and implicit solutions. Numerical stability.

CMSE/CSE 822 Parallel Computing— Core principles, techniques, and use of parallel computation using modern supercomputers. Parallel architectures. Parallel programming models. Principles of parallel algorithm design. Performance analysis and optimization.

CMSE 823 Numerical Linear Algebra— Methods in modern numerical linear algebra for solving linear systems, least squares problems, and eigenvalue problems. Efficiency and stability of algorithms in numerical linear algebra.

B Additional Elective Courses

B.1 Astronomy & Astrophysics

AST 850 Electrodynamics of Plasmas— Plasma kinetic and macroscopic plasma transport theory. Electromagnetic wave propagation and charged particle diffusion processes in plasma. Electromagnetic energy absorption via elastic and inelastic collisions. DC, RF, and microwave discharges.

AST 860 Gravitational Astrophysics— Experimental foundations, theory, and applications of gravitational physics and general relativity. Tests of the equivalence principle, modern solar system tests of general relativity, Schwarzschild metric, Hawking effect, Einstein's field equations.

B.2 Physics

PHY 950 Data Analysis Methods— Tools and methods used for analyzing data in large experiments.

B.3 Statistical and Computational

ME 835 Turbulence Modeling and Simulation— Basic turbulence theory. Transport equations for calculations of turbulent flows. Current status of modeling and simulation of turbulent flows. Direct numerical simulation. Reynolds-averaged simulations. Large eddy simulation. Probability density function methods in turbulence.

ME 840 Computational Fluid Dynamics and Heat Transfer— Theory and application of finite difference and finite volume methods to selected fluid mechanics and heat transfer models including the full potential flow model, the systems of Euler and Navier-Stokes equations, and turbulence. Grid generation techniques.

STT 802 Statistical Computation— Computational techniques commonly used in Statistics. Matrix decompositions. Least squares and Least Absolute Deviations. Solution of nonlinear equations. Optimization techniques including the EM algorithm and constrained optimization. Numerical integration. Generation of random numbers and stochastic simulation. Implementation in statistical software.

STT 874 Introduction to Bayesian Analysis— Bayesian methods including empirical Bayes, hierarchical Bayes and nonparametric Bayes, computational methods for Bayesian inference including the Gibbs Sampler and Metropolis-Hastings method, and applications.