Computational Science: Astrophysics

Institute for Theoretical Astrophysics, University of Oslo

Planned start: Fall 2018

Why Astrophysics

Roughly speaking, astrophysics is the study of anything and everything outside the Earth's domain, including the Moon, the Planets, interplanetary space and the Solar Wind, the Sun, the stars, the Milky Way, Galaxies, Galaxy Clusters, and the birth, evolution and structure of the Universe itself. Astrophysics is a field where there is little "laboratory" work, instead contact with reality must necessarily go via various remote sensing methods. This is perhaps the reason that astrophysicsts were amongst the first to develop numerical techniques to model quite complicated systems and to use high performance computers as a laboratory, or test bed, to confront their theories with observational reality.

In particular, at the Institute of Theoretical Astrophysics (ITA), computational science is mainly concentrated on three subjects: solar atmospheric modeling, extragalactic studies, and the evolution of structure in the Universe.

Solar Physics

Sufficiently stable to nurture life during the last 4 billion years, and modern humans the last 100,000 years, the Sun is nevertheless a variable star. While the total solar irradiance only varies of order 0.1% during the 11-year solar cycle, the high-energy portion of the solar output can vary by several orders of magnitude on timescales of minutes. Solar activity - sun spots and active regions, UV and X-ray emission, the million degree corona, flares, coronal mass ejections, the acceleration of energetic particles - is increasingly interfering with human activity as our society's dependence on sensitive electronic equipment grows and as we venture beyond the Earth's magnetosphere and into the solar system proper. There is thus a pressing need to understand the workings of the energetic Sun.

At the ITA we have a goal of solving the problems of understanding and explaining the active sun. This means that we wish to build numerical models of the solar atmosphere good enough that we can construct synthetic spectral lines and images that can be directly compared with the observations. We have access to the best observables; members of the solar group at the ITA are Co Investigators on ESA's SOHO mission, NASA's IRIS and SDO missions,

and JAXA's Hinode mission, as well as having 42 days of observing time at the worlds premier solar telescope, the Swedish 1-meter Solar Telescope on La Palma (Canary Island). To model the Sun we have constructed the Bifrost code, currently the worlds most advanced code for modeling the solar chromosphere and corona, and a code that we plan to expand to incorporate more advanced physics such as Generalized Ohm's Law, Multi-Fluid dynamics, and particle effects on relevant subregions. This set of tools gives us a fighting chance of solving the puzzles that confront us, but also the chance of involving our students in exciting work at the forefront of science with a mix of observational, theoretical, and/or numerical tasks.

Extragalactic astronomy and Cosmology

Galaxies are the building blocks of the Universe. Our home Galaxy, the Milky Way, hosts tens of billions of stars like the Sun, and the Universe contains about one to two hundred billions of galaxies. Galaxies come with different varieties, some with grand design spiral arms like the Milky Way, some with the shape of an ellipsoidal, and still some galaxies look completely irregular. Virtually all large galaxies (including the Milky Way) harbour supermassive black holes (SMBHs) at their centre. The vast space between galaxies are filled with gaseous intergalactic medium. Following the underlying dark matter structure, the gas accretes onto galaxies, and fuels the star formation and black hole growth within them. In turn, the stars and supermassive black holes inject energy, momentum, radiation and metals (elements with atomic number larger than Helium) into the surrounding gas which impact the subsequent accretion and star formation. When and how did the first galaxy form from the initial quantum perturbations? How do galaxies evolve throughout the cosmic history? What causes the galaxy population to be so diversified? And how do supermassive black holes form and co-evolve with the host galaxies? How did the radiation from first stars and black holes transform the intergalactic gas? These are some of the central questions we want to address in modern cosmology.

Simulating such complex and non-linear systems numerically is a highly challenging task, one needs to not only cover a large dynamic range, but also model simultaneously many physical processes (gravity, hydrodynamics, turbulence, star formation, black hole formation, radiation, magnetic field and perhaps cosmic rays etc.). At the ITA, we simulate cosmological galaxy formation with state-of-the-art hydrodynamic codes and sophisticated models of physical processes, including the one that has successfully simulated the world's first realistic Milky Way-like galaxy. We also developed a world-leading radiative transfer code to produce synthetic observations to confront simulations with the data. We have local expertise on observations of high-redshift galaxies using first-rate gravitational lensing data from the large Sloan Giant Arc Survey and the future Euclid satellite, as well as multi-wavelength data from major ground-based and space telescopes like HST, Keck, ALMA, GAIA and the upcoming JWST on galaxies at both early Universe and current epoch. It is the golden age for

cosmology and extragalactic astronomy and students will be involved in exciting and fruitful projects at the ITA.

OK, sounds like fun, but is it actually possible to get a job with a degree in astrophysics?

Successful astrophysics students have learned a large variety techniques to attack abstract problems. These are skills that have applications far outside of the study of "stars". To give you a taste of possible careers we have compiled a set of interviews of our alumni where they explain the relevance of their educations to their careers.

Structure and courses

The table here is an example of a suggested path for a Master of Science project, with course work the first year and thesis work the last year.

	10 ECTS	10 ECTS	10 ECTS
4th semester	Master thesis	Master Thesis	Master Thesis
3rd semester	Master thesis	Master Thesis	Master Thesis
2nd semester	Master courses	Master courses	Master courses
1st semester	Master courses	Master courses	Master courses

This program is very flexible in its structure and students may opt for starting with their thesis work from the first semester and scatter the respective course load across all four semesters. Depending on interests and specializations, there are many courses on computational science which can make up the required curriculum of course work. Furthermore, courses may be broken up in smaller modules, avoding thereby the limitation of 10 ECTS per course only. Some of these courses are listed below.

Courses. Depending on specialization, the following courses that can be included as part of the compulsory 60 ECTS needed for a Master of Science degree are described here.

Graduate Certificates. The program plans to offer graduate certificates in

- Three of the courses with label CS-MATH gives a certificate in Computational Mathematics

- Three of the courses with label CS-PHYS gives a certificate in Computational Physics, Astrophysics, Chemistry, Materials Science and Geoscience

- Three of the courses with label CS-BIO gives a certificate in Computational life science.

- Three of the courses with label CS-INF gives a certificate in High-performance computing.

Dual Degrees. The program plans to offer dual degrees (more text to come)

Description of learning outcomes

The power of the scientific method lies in identifying a given problem as a special case of an abstract class of problems, identifying general solution methods for this class of problems, and applying a general method to the specific problem (applying means, in the case of computing, calculations by pen and paper, symbolic computing, or numerical computing by ready-made and/or self-written software). This generic view on problems and methods is particularly important for understanding how to apply available, generic software to solve a particular problem.

Computing competence represents a central element in scientific problem solving, from basic education and research to essentially almost all advanced problems in modern societies. Computing competence is simply central to further progress. It enlarges the body of tools available to students and scientists beyond classical tools and allows for a more generic handling of problems. Focusing on algorithmic aspects results in deeper insights about scientific problems.

The learning outcomes are subdivided in three general categories, knowledge, skills and general competence.

- **Knowledge**: A candidate from this program

  - has deep knowledge of the scientific method and computational science at an advanced level, meaning that the candidate

    1. has the ability to understand advanced scientific results in new fields
    2. has fundamental understanding of methods and tools
    3. can develop and apply advanced computational methods to scientific problems
    4. is capable of judging and analyzing all parts of the obtained scientific results
    5. can present results orally and in written form as scientific reports/articles
    6. can propose new hypotheses and suggest solution paths
    7. can generalize mathematical algorithms and apply them to new situations
    8. can link computational models to specific applications and/or experimental data
    9. can develop models and algorithms to describe experimental data
    10. masters methods for reproducibility and how to link this to a sound ethical scienfitic conduct
    11. has a thorough understanding of how computing is used to solve scientific problems

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12. knows fundamental algorithms in computational science

– has a fundamental understanding and knowledge of scientific work, meaning that

1. the candidate can develop hypotheses and suggest ways to test these
2. can use relevant analytical, experimental and numerical tools and results to test the scientific hypotheses
3. can generalize from numerical and experimental data to mathematical models and underlying principles
4. can analyze the results and evaluate their relevance with respect to the actual problems and/or hypotheses
5. can present the results according to good scientific practices

- **Skills**: A candidate from this program

– has a deep understanding of what computing means, entailing several or all of the topics listed below

1. knows the most fundamental algorithms involved, how to optimize these and perform statistical uncertainty quantification
2. has overview of advanced algorithms and how they can be accessed in available software and how they are used to solve scientific problems
3. has knowledge and understands high-performance computing elements: memory usage, vectorization and parallel algorithms
4. can use effeciently high-performance computing resources, from compilers to hardware architectures
5. understands approximation errors and what can go wrong with algorithms
6. has knowledge of at least one computer algebra system and how it is applied to perform classical mathematics
7. has extensive experience with programming in a high-level language (MATLAB, Python, R)
8. has experience with programming in a compiled language (Fortran, C, C++)
9. has experience with implementing and applying numerical algorithms in reusable software that acknowledges the generic nature of the mathematical algorithms
10. has experience with debugging software
11. has experience with test frameworks and procedures
12. has experience with different visualization techniques for different types of data
13. can critically evaluate results and errors

14. can develop algorithms and software for complicated scientific problems independently and in collaboration with other students
15. masters software carpentry: can design a maintainable program in a systematic way, use version control systems, and write scripts to automate manual work
16. understands how to increase the efficiency of numerical algorithms and pertinent software
17. has knowledge of stringent requirements to efficiency and precision of software
18. understands tools to make science reproducible and has a sound ethical approach to scientific problems

- **General competence**: A candidate from this program

  - is able to develop professional competence through the thesis work, entailing:
    1. mature professionally and be able to work independently
    2. can communicate in a professional way scientific results, orally and in written form
    3. can plan and complete a research project
    4. can develop a scientific intuition and understanding that makes it possible to present and discuss scientific problems, results and uncertainties

  - is able to develop virtues, values and attitudes that lead to a better understanding of ethical aspects of the scientific method, as well as promoting central aspects of the scientific method to society. This means for example that the candidate
    1. can reflect on and develop strategies for making science reproducible and to promote the need for a proper ethical conduct
    2. has a deep understanding of the role basic and applied research and computing play for progress in society
    3. is able to promote, use and develop version control tools in order to make science reproducible
    4. is able to critically evaluate the consequences of own research and how this impacts society
    5. matures an understanding of the links between basic and applied research and how these shape, in a fundamental way, progress in science and technology
    6. can develop an understading of the role research and science can play together with industry and society in general
    7. can reflect over and develop learning strategies for life-long learning.

By completing a Master of Science thesis, the candidate will have developed a critical understanding of the scientific methods which have been studied, has a better understanding of the scientific process per se as well as having developed perspectives for future work and how to verify and validate scientific results.

Admission criteria: Astrophysics

The program has a minimum course requirement of 120 ECTS (European Credit Transfer System) at the undergraduate level (bachelor degree or equivalent) in astrophysics, bioscience, chemistry, computer science and informatics, geoscience, mathematics, materials science, mechanics and physics.

1. Of these 120 ECTS, 40 ECTS have to include basic mathematics and programming courses, equivalent to the University of Oslo mathematics courses MAT1100, MAT1110, MAT1120 and at least one of the corresponding computing and programming courses INF1000/INF1110 or MAT-INF1100/MAT-INF1100L/BIOS1100/KJM-INF1xxx.

2. The remaining 80 ECTS have to be within at most two of the fields of astrophysics, bioscience, chemistry, computer science and informatics, geoscience, mathematics, materials science, mechanics and physics. 40 of these 80 ECTS have to be advanced undergraduate courses at the 2000 and 3000 level and a minimum of 20 ECTS must be at the 3000 level within physics/material science/astrophysics/informatics/mathematics/mechanics.

3. An average mark C (European grading scale) is required for the 40 ECTS in mathematics and programming (corresponding to the University of Oslo courses MAT1100, MAT1110, MAT1120 and the corresponding computing and programming courses INF1000/INF1110 or MAT-INF1100/MAT-INF1100L/BIOS1100/KJM-INF1xxx or similar courses) and the 40 ECTS at the 2000 and 3000 level. A minimum of 20 ECTS must be at the 3000 level within physics/material science/astrophysics/informatics/mathematics/mechanics.

Study abroad and international collaborators

Students at the University of Oslo may choose to take parts of their degrees at a university abroad. The University of Oslo has exchange agreements with other universities in different parts of the world. The MN Faculty has additional exchange agreements with many universities abroad.

Students in this program have a number of interesting international exchange possibilities. The involved researchers have extensive collaborations with: **add text**

Career prospects

Candidates who are capable of modeling and understanding complicated systems in natural science, are in short supply in society. The computational methods

and approaches to scientific problems students learn when working on their thesis projects are very similar to the methods they will use in later stages of their careers. To handle large numerical projects demands structured thinking and good analytical skills and a thorough understanding of the problems to be solved. This knowledge makes the students unique on the labor market.

Career opportunities are many, from research institutes, universities and university colleges and a multitude of companies. Examples include IBM, Hydro, Statoil, and Telenor. The program gives an excellent background for further studies, with a PhD as one possible goal.

The program has also a strong international element which allows students to gain important experience from international collaborations in science, with the opportunity to spend parts of the time spent on thesis work at research institutions abroad.