Astrophysical Radiation (PHYS5526)
Syllabus for Fall 2025

Instructor Information

Instructor: Prof. James Aguirre
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Course Content

From the course catalog:

> This is a course on the theory of the interaction of light and matter designed primarily for graduate and advanced undergraduate students to build the basic tools required to do research in astrophysics. Topics to be discussed include structure of single- and multi-electron atoms, radiative and collisional processes, spectral line formation, opacity, radiation transfer, analytical and numerical methods, and a selection of applications in astrophysics based on student research interest.

The course begins with a review of the classical theory of electromagnetism (Maxwell's equations) and some basics of the generation and description of electromagnetic radiation, demonstrating some simple interactions of radiation with free and bound classical electrons (Thomson scattering). We then discuss the important case of thermal ("blackbody") radiation. We discuss a phenomenological description of radiation ("specific intensity") and bulk properties of matter which are combined into the important radiative transfer equation. We then turn to the astrophysically important state of matter of the plasma, and its unique properties, and discuss the emission from hot plasma (bremsstrahlung). We discuss the dynamics of charged particles moving at relativistic speeds, and the relativistic radiation processes of Compton scattering, synchrotron radiation, and inverse Compton scattering. We then review the quantum mechanical description of the atom and the description of radiation coupling the classical EM field to a quantum mechanical atom or molecule. This gives us a complete theory of spectroscopy and line emission and absorption, which we explore in detail in the context of stellar atmospheres. Finally, we look at molecular emission and the importance of dust emission, absorption, and scattering in the interstellar medium.

Grading

As discussed further in the "Course Philosophy" below, this is a graduate-level course with a view towards imparting not just domain-specific knowledge, but also relevant skills for advanced study and research in STEM fields.

Each week will follow a similar format. Prior to a given week's classes, **readings** and and a (short) reading quiz will be assigned, with the **reading quizzes** due *before* the relevant lecture. This is to make sure you have some background with the material before we begin discussing it. In general, one class per week will be devoted to lecture and the second to an in-class exercise done in groups. The **in-class exercises** will emphasize using numerical solutions in Jupyter notebooks using Python as well as providing opportunity for informal discussion and questions. The in-class exercises will be graded individually (each student turns in their own), though you are allowed to work on them together. The idea is to finish most or all of the exercise in-class, but unfinished portions can be finished outside of class. Four **homework** assignments will consist of 2 - 3, primarily analytical, questions to emphasize the topics covered in the readings and lecture but not brought out in the in-class exercises. The **final project** is a research-like paper on a particular astrophysical object or environment of your choosing. The paper will describe the object based on references you find in the research literature. The paper will describe the relevant physical processes that produce the radiation from that object, and the mathematical description of the spectrum of radiation produces. You will then calculate a spectrum for your particular object and compare it against a spectrum from the literature. To help you formulate and make progress on the final project, there will be two "**midterms**": the first "midterm" is a 30-minute individual meeting where we can get to know each other a bit more, and discuss your ideas for the project, and then you will produce a two-page written outline of the proposed project. The second midterm is a more detailed check-in on the calculations you are doing and whether you are having difficulty.

A breakdown of the grading and proposed schedule of topics and assignments are given below.

Reading quizzes	12	20%
In-class exercises	12	30%
Homework	4	20%
Midterms	2	5% each
Final project		20%

	Date			In-class	Due
1	Tue	Aug	26	Introduction	
2	Thu	Aug	28	ICE1: Electromagnetic Units	
3	Tue	Sep	2	Radiation basics	RQ1
4	Thu	Sep	4	ICE2: Thermal Radiation	
5	Tue	Sep	9	Radiative Transfer I	RQ2
6	Thu	Sep	11	ICE3: the Gray Atmosphere	HW1
7	Tue	Sep	16	Radiative Transfer II	RQ3
8	Thu	Sep	18	ICE4: AGN Accretion Disks (example project)	
9	Tue	Sep	23	Plasmas	RQ4
10	Thu	Sep	25	ICE5: Plasma Physics	
11	Tue	Sep	30	Bremsstrahlung	RQ5
12	Thu	Oct	2	ICE6: HII regions	MT1
13	Tue	Oct	7	Relativistic Dynamics	HW2
14	Tue	Oct	14	Synchrotron Radiation	RQ6
15	Thu	Oct	16	ICE7: the Synchrotron Spectrum	
16	Tue	Oct	21	High Energy Processes	RQ7
17	Thu	Oct	23	ICE8: Inverse Compton Scattering	
18	Tue	Oct	28	Atomic structure	RQ8
19	Thu	Oct	30	ICE9: EM & QM in atoms	MT2
20	Tue	Nov	4	Spectroscopy	RQ9
21	Thu	Nov	6	ICE10: Absorption Line Formation	HW3
22	Tue	Nov	11	Stellar Atmospheres	RQ10
23	Thu	Nov	13	ICE11: the Curve of Growth	
24	Tue	Nov	18	Molecular Lines	RQ11
25	Thu	Nov	20	ICE12: CO and its SLED	
26	Tue	Nov	25	Dust	RQ12
27	Tue	Dec	2	ICE13: Dust and the ISM	
28	Thu	Dec	4	Review and final thoughts	HW4

Course Motivation and Philosophy

This course focuses on the theory and phenomenology of the production of light (photons) and the physics of photon propagation in astronomical environments. This is an extremely important topic for observational astronomy: essentially all of the information we get from stars and galaxies is in the form of light. Understanding light production and propagation allows us to infer the physical conditions of the source of light through observations.

Basically, the idea behind this course to show how we can answer the question, "For a given astrophysical object or scenario (for which I have some theoretical model), what is the nature of the electromagnetic radiation that emerges from that object? In particular, what is the intensity, spectral distribution, and polarization of that radiation?"

The inverse problem of inferring from radiation properties the properties of the emitting source is a topic for a different course, since it requires us to address the difficulties in radiation measurement, as well as the limitations of inverting the generally non-unique relation between emitted light and physical properties.

Goals for the Course

This is a graduate level class, and therefore we want to develop some "graduate level" skills. Among other things, I have found that this means the ability to cut through distractions, find necessary information, deal with some level of ambiguity and imprecision, understand when you don't understand, and figure out how to fill in information that has not been provided. Some broad "soft skills" we want to work on:

- Finding the key information in a sea of things which are not relevant
- Gaining a broad understanding even when not getting all the details
- Being able to devise tests of your understanding
- Being able to catch when a reference contains errors (which happens, but we want to distinguish that from when you think there's an error, but you've actually misunderstood something)
- Recognizing when one statement clearly follows from the previous one through relatively simple (though omitted) steps, and where the author has truly brought in additional information without derivation or context (which also totally happens!)

There are also skills that break down along more traditional lines, and I outline some of these below.

Reading

We want to work on being able to read difficult material and still get something from it. This includes being able to follow and do fairly sophisticated derivations and to understand the limitations of the approximations made and when various formulas are likely to be appropriate. The readings are the backbone of this course and will be related to the homework and the final project. In this course, we're going to practice reading by doing it and then by discussing things which are difficult. The readings are selected to cover useful and important topics, but in almost certainly too long, too difficult, and contain a lot of information which we won't actually use. (And that's OK.) They have a variety of styles and of course don't have a consistent notation (or even sets of units) between them.

For every reading assignment, we will have a reading quiz to make sure you are reading the material and thinking (a bit) about it before we meet. You answers will then guide the discussion in class. The readings will also help you select a topic for the final project and to learn the relevant mathematics and physics to calculate a spectrum for a given astrophysical object.

Writing

We also want to be able to write well. Science is only science if it is communicated. Some of this communication, of course, is done through speaking (lectures and talks) and some via non-linguistic forms (graphs, equations). But writing clearly is still a big part of this, and scientists are generally poor at it. Some part of good scientific writing is simply following the rules from English class, but the more important part is learning the art of writing precisely. Most scientific writing is short on adjectives and adverbs, but is very carefully constructed to convey information in as clear and unambiguous a manner as possible. Consequently, it is often dull. We are going to practice writing in the reading quizzes (I will largely ask open-ended questions) and by working on your project.

Calculation

Sometimes you will find that someone has already derived precisely the equation you need to calculate a quantity you're interested in. But in most research work, you will need to do some analytic manipulation. And we also need to be able to go from analytic equations to actual numbers we can compare to experiments (which is another skill) and we're going to lean heavily on doing numerical calculations in Python.

Presentation of data

The art of presenting data and information visually, whether via graphs, movies, or schematics, is a key part of the scientific communication process and takes practice. We rarely want to compute just a single number, but rather want to compute the complicated functional dependence on a range of parameters and display this in a meaningful way.