# Our Magnetic Universe: An Introduction to Astrophysical Magnetism

Spring 2026; Astronomy UN3XXX
MW 1:10pm-2:25pm
1332 Pupin Laboratories
3 Points

**Instructor:** Ryan Golant (feel free to call me Ryan – no title or honorific preferred)
**Office:** [Redacted]
**Email:** [Redacted]
**Phone:** [Redacted]
**Calendly:** https://calendly.com/ryangolant
**Office Hours:** Formally, MW 2:30pm-3:30pm (i.e., the hour after class time) in Pupin 1332. However, given advanced notice, I am happy to meet with you at an alternative time. You may contact me at any time via email, or you may schedule a meeting (in person or on Zoom) via Calendly.

## Course Description:

Magnetic fields are ubiquitous throughout the Universe. At all scales – from the tiniest planetesimals forming out of protoplanetary disks to the longest filaments threading galaxy clusters – magnetic fields shape our cosmos. Thus, **if we wish to fully understand our Universe, we must first understand the physics of these magnetic fields and of the plasmas that host them.** In the first half of this course, we will develop a quantitative framework for describing the behavior of astrophysical plasmas and their intimate interplay with magnetic fields; in the second half, we will apply this framework to elucidate the role that magnetic fields play in a wide array of astrophysical systems, from our own Earth to the vast cosmic web. Along the way, we will explore a variety of analytical, numerical, and observational techniques used in cutting-edge research on astrophysical magnetism. By the end of this course, we should be equipped with the skills necessary to distill and communicate key ideas from both secondary and primary literature on astrophysical magnetic fields.

**Prerequisites:** Working knowledge of **vector calculus** (e.g., gradient, divergence, curl; Stokes' theorem and Gauss' theorem) – as taught in Mathematics UN1202 or UN1205 – is required. Familiarity with **electromagnetism** (e.g., Maxwell's equations; the Lorentz force) and with **thermodynamics** (e.g., the laws of thermodynamics; properties of perfect/ideal gases) – as taught in Physics UN1602 – is strongly recommended. Basic familiarity with Python is beneficial, but not required.

## Course Learning Objectives:

By the end of this course, you should be able to…

1) Quantitatively **describe the salient properties of astrophysical plasmas** and the interplay between plasmas and magnetic fields.
2) Apply both the fluid and kinetic descriptions of plasma to **elucidate the role that magnetic fields play in a wide range of astrophysical systems**, from planetary scales to cosmological scales.
3) **Describe the prevalent analytical, numerical, and observational techniques** used in modern research on astrophysical magnetism.
4) Extract and **explain key results from primary and secondary literature** on plasma astrophysics and astrophysical magnetic fields.
5) Clearly **communicate scientific concepts** through both writing and speaking.

## Course Materials:

Required Text: Choudhuri AR. *The Physics of Fluids and Plasmas: An Introduction for Astrophysicists*. Cambridge University Press; 1998. (freely available online through the Columbia libraries at https://www.cambridge.org/core/books/physics-of-fluids-and-plasmas/8A235D6F1D9DA51F05237D42BDFEFD06)

Recommended Texts (I will share excerpts from these texts where necessary):

- Griffiths, DJ. *An Introduction to Electrodynamics*. Pearson Education, Inc.; 2013.
- Kulsrud, RM. *Plasma Physics for Astrophysics*. Princeton University Press; 2005.

I will also be sharing my own lecture notes via CourseWorks; while these notes may have substantial overlap with the Choudhuri text, they will be tailored to better fit the context of our class. Additionally, where appropriate (e.g., for problem sets and in preparation for your class presentations), I will post excerpts from other textbooks, review articles, or published papers on CourseWorks.

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## Teaching Philosophy: Why am I teaching this course?

In creating and teaching this course, I hope to pique your interest in the important and wide-reaching topic of astrophysical magnetism, as well as in the broader landscapes of plasma astrophysics and fluid dynamics; these topics are vitally important for research in astronomy and astrophysics, yet they are typically only taught at the graduate level (as is the case at Columbia). Additionally, in teaching this course, I hope to learn *from* *you*; as a new instructor teaching this course for the first time, I welcome any and all feedback on how I could be a more effective teacher and how I could improve this course. To facilitate this, I aim to create a safe and accessible learning environment in which everyone feels empowered to contribute their thoughts. Much of this course's content – especially in the second half of the course – is flexible; if there is a specific topic you would like to see covered in this course, please let me know. Throughout the semester, I will be explicitly soliciting feedback through various channels, allowing you to provide input on course content, course policies, class structure, and my own teaching.

**Throughout this course, I expect you to…**

- Come to class on time and actively participate in class to the best of your abilities.
- Complete all assigned work – including any necessary pre-class reading – in a timely manner.
- Respect the contributions of your peers.
- Be transparent with me about any issues that may affect your ability to perform optimally in this class.
- Provide regular feedback on any and all aspects of the course so that we may work towards establishing an optimal learning environment.

**Throughout this course, you should expect me to…**

- Come to class on time and be fully prepared for every class session.
- Assign no more than 5 hours of work outside of class each week.
- Grade and provide feedback on all submitted assignments in a timely manner.
- Facilitate stimulating full-class discussions and worthwhile small-group activities to the best of my abilities.
- Respect the ideas and contributions of all students.
- Adapt my teaching methods to suit the needs of the greatest number of students.
- Respond meaningfully and promptly to any and all student input.

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**What to expect during class time:**

For much of the course, classes will be lecture-based, with short breakout discussions or group activities to reinforce lecture material. In the first half of the course, I aim to introduce the principles of plasma physics in just enough depth to prepare us for our exploration of astrophysical magnetism in the second half of the course; in this regard, the treatment of plasma physics in this course will be less rigorous and less comprehensive than one might find in a standard course on plasma physics (e.g., Applied Physics E6101) or astrophysical fluid dynamics (e.g., Astronomy GR8003). In the second half of the course, seven class periods are set aside for each of *you* to lead the class; see the description of the "Class Presentation" below for more details.

## **Grade Breakdown**:

30% Problem sets
20% Midterm exam
20% Class presentation
20% Final exam
10% Participation

## **Description of Assignments**:

*Targeted Course Learning Objectives (CLOs, listed above) are highlighted in **purple***

Problem Sets:
Because we have limited time in class, I will use problem sets to both supplement and complement class material. For example, problem sets may ask you to apply a concept learned in class to a specific physical scenario **(CLO #2)**, complete an interesting or enlightening derivation **(CLO #1)**, read and interpret an excerpt from a textbook or a published paper **(CLO #4)**, or interact with simulations or observational data via Jupyter Notebooks **(CLO #3)**. I aim to make the problem sets as pedagogical as possible by providing ample context and guidance for the problems, so do not panic if the problem sets look lengthy (but do let me know if they are taking an excessive amount of time).

There will be around **eight problem sets throughout the semester**, assigned roughly every three class periods and **due by 11:59pm on the day that the next problem set is posted** (see Detailed Course Schedule below); you may submit a hardcopy of your solutions to the inbox outside my office, or you may scan your solutions and upload them to CourseWorks as a PDF. Problem sets will be graded (with feedback) within a week of submission.

Midterm Exam:
We will have a **take-home midterm exam** during the week of March 9; the exam will be **posted on CourseWorks after class on Monday, March 9** and will be **due at 11:59pm on Thursday, March 12**. The exam will be comprehensive and open-notes, covering all the material from the first half of the course **(CLO #1)**.

Class Presentation:
One of the best ways to reinforce your understanding of a topic is to teach others about that topic. In the second half of the course, **seven class periods are set aside for *you* to lead**. With a partner, you will choose an astrophysical system in which magnetic fields are important and you will teach the class about that system; seven suggested

topics are listed on the Course Schedule (see classes highlighted in blue), though you are welcome to propose your own topics. **The modality by which you teach the class is up to you** – you may lecture at the blackboard, present a PowerPoint, distribute a handout, or do something else entirely; you should aim for your lesson to be around 45 minutes. You will also submit a homework problem to be included on the next PSet.

**Presentation topics must be chosen by Friday, February 27**; prior to the 27th, I will upload a list of suggested resources for each topic to CourseWorks, including a breakdown of each topic into subtopics to help you and your partner appropriately split up the work. To assist you through the process of creating your presentation, **I will meet with you both three weeks and one week prior to your presentation date** to check in on your progress and to provide guidance.

Ultimately, your presentation grade will be based on your ability to clearly and accurately communicate the material at an appropriate level **(CLO #4, #5)**, to use both quantitative and qualitative descriptions where relevant (drawing from analytical, numerical, and observational results; **CLO #2, #3**), and to connect your presentation to the larger themes of the course; see the Class Presentation Rubric on CourseWorks for more details.

Final Exam:

This course's final exam will assess **all of the course's learning objectives**, including both mastery of content knowledge and mastery of the skills required to parse a scientific paper and effectively communicate its results. For the final exam, you will select one paper on astrophysical magnetism from a brief list of papers that I will share on Monday, April 27 (two weeks prior to final exams week). During the exam period (**Monday May 11 - Friday May 15**), **we will schedule a one-on-one meeting during which we will discuss your chosen paper and its connection to class material**. To prepare for this discussion, you will also write up a brief (~3 paragraph) summary of the paper's context, methods, and results, to be submitted before we meet. Your final exam grade will be based on your ability to clearly and accurately explain the key ideas of the paper **(CLO #4, #5)** and to answer relevant questions **(CLO #1, #2, #3)**; see the Final Exam Rubric on CourseWorks.

Participation:

Communicating with others is a vital part of being an astronomer; at conferences, within collaborations, or simply with your advisor, asking questions and engaging in discussions is necessary to acquire knowledge, to form connections with other astronomers, and to advance the field as a whole. As such, **participation – emulating what is required in a professional astronomer's career – is integral to this course (CLO #5).**

Within this course, "participation" will include coming to class on time, engaging in in-class activities, asking questions (to both me and your peers), answering questions (from both me and your peers), and completing “exit ticket” reflections at the end of each class period**.** I expect everyone to engage in these tasks to the best of their abilities, and I will try my best to provide accommodations to facilitate participation (e.g., by providing access to a semi-anonymized online discussion forum if you do not wish to ask a question in front of your peers or if you wish to ask a question outside of class).

Since different students may be at different levels of comfort or ability to participate, **participation will be evaluated based on an individualized, single-point rubric** (see the Participation Rubric on CourseWorks). At the start of the course, you will devise a set of goals for class participation, and we will subsequently meet one-on-one three times throughout the semester to check in on how the course has been going, to discuss your level of participation, and to revise your goals moving forward; at each of these meetings, we will discuss the extent to which you met your goals for that portion of the course and, **together, we will assign a participation grade accordingly**. You will receive three participation grades throughout the semester (one for each meeting); these grades will be weighted progressively – 10% of the total participation grade for the first grade, 30% for the second, and 60% for the third – to emphasize growth throughout the course.

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# **Detailed Course Schedule**

Classes highlighted in **blue** are reserved for student presentations. Unless otherwise noted, assignments highlighted in **red** are due by 11:59pm that evening.

| | Monday | Wednesday |
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| **Week 0** (Jan. 19) | **No class:** Martin Luther King, Jr. Day | Topic: **Why should we care about astrophysical magnetic fields?**<br><br>Reading: Class syllabus<br><br>Notes: Syllabus annotation due in class (see CourseWorks announcement) |
| **Week 1** (Jan. 26) | Topic: **What is a magnetic field?**<br><br>Reading: Griffiths 5.1-5.3, 7.3<br><br>Notes: | Topic: **What is a plasma?**<br><br>Reading: Choudhuri 11.1-11.3<br><br>Notes: Problem Set #1 posted |
| **Week 2** (Feb. 2) | Topic: **Is plasma a fluid or a collection of particles?**<br><br>Reading: Choudhuri 1<br><br>Notes: | Topic: **What is a fluid?**<br><br>Reading: Choudhuri 4.1-4.2<br><br>Notes: |
| **Week 3** (Feb. 9) | Topic: **What is magnetohydrodynamics (MHD)?**<br><br>Reading: Choudhuri 14.1-14.2<br><br>Notes: Problem Set #2 posted; Problem Set #1 due | Topic: **How does viscosity affect an MHD plasma?**<br><br>Reading: Choudhuri 5.1-5.2, 5.4<br><br>Notes: |

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| **Week 4**<br>(Feb. 16) | Topic: **How does resistivity affect an MHD plasma?**<br><br>Reading: Choudhuri 13.4, 13.6, 15.1<br><br>Notes: | Topic: **How does magnetic reconnection dissipate magnetic fields?**<br><br>Reading: Choudhuri 15.2<br><br>Notes: Problem Set #3 posted; Problem Set #2 due |
| **Week 5**<br>(Feb. 23) | Topic: **How do waves behave in an MHD plasma?**<br><br>Reading: Choudhuri 6.1-6.2, 14.5, 14.3.2<br><br>Notes: | Topic: **How do shock waves form in an MHD plasma?**<br><br>Reading: Choudhuri 6.4-6.5; Kulsrud 6.3<br><br>Notes: Class presentation topic must be chosen and emailed to Ryan by Friday, Feb. 27 |
| **Week 6**<br>(March 2) | Topic: **How are astrophysical magnetic fields amplified and sustained?**<br><br>Reading: Choudhuri 16.1-16.2, 16.4; Chapters 1 and 2.3 in Rincon *Dynamo Theories* (2019)<br><br>Notes: Problem Set #4 posted; Problem Set #3 due | Topic: **How are astrophysical magnetic fields created?**<br><br>Reading: Introduction to Zhou et al. *Magnetogenesis in a Collisionless Plasma: From Weibel Instability to Turbulent Dynamo* (2023); Sections I-III in Schoeffler et al. *The generation of magnetic fields by the Biermann battery and the interplay with the Weibel instability* (2016)<br><br>Notes: |
| **Week 7**<br>(March 9) | Topic: **How are the microscopic and macroscopic properties of plasmas connected?**<br><br>Reading: Choudhuri 3.7, 11.7<br><br>Notes: Take-home midterm posted on CourseWorks; Problem Set #4 due | Topic: **[free period – overflow from previous classes, if necessary]**<br><br>Reading: N/A<br><br>Notes: Continue to work on take-home midterm (due Thursday, March 12, 11:59pm) |

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| **Week 8** (March 16) | **No class: Spring Break!** | **No class: Spring Break!** |
| **Week 9** (March 23) | Topic: **How do we simulate MHD plasmas on a computer?**<br><br>Reading: Romain Teyssier's notes on Finite Volume Methods (2023); Chris White's notes on Finite-Volume MHD (2023)<br><br>Notes: | Topic: **How do we simulate kinetic plasmas on a computer?**<br><br>Reading: Smilei code documentation (https://smileipic.github.io/Smilei/Understand/algorithms.html); Tristan v2 code documentation (https://princetonuniversity.github.io/tristan-v2/docs/code/pic-concept/)<br><br>Notes: |
| **Week 10** (March 30) | Topic: **How do we observe astrophysical magnetic fields?**<br><br>Reading: Chapters 11.1-11.3, 12.1, 26.3, and 5.3 in Draine *Physics of the Interstellar and Intergalactic Medium* (2011)<br><br>Notes: Problem Set #5 posted | Topic: **Why does the Earth have a magnetic field and why is this important?**<br><br>Reading: Chapters 4.1-4.2 and 5.1 in Rincon *Dynamo Theories* (2019); Choudhuri 10.4; Kulsrud 2.6<br><br>Notes: |
| **Week 11** (April 6) | Topic: **Space weather: How do magnetic fields power solar activity?**<br><br>Reading: Choudhuri 4.4, 14.6-14.7, 14.9.2, 15.5<br><br>Notes: | Topic: **How do magnetic fields affect the formation of stars and planets?**<br><br>Reading: Choudhuri 14.8-14.9; Kulsrud 3.3.1-3.3.2, 3.3.4<br><br>Notes: Problem Set #6 posted; Problem Set #5 due |
| **Week 12** (April 13) | Topic: **What are cosmic rays and how are they influenced by magnetic fields?**<br><br>Reading: Kulsrud 12.1-12.6 | Topic: **What role do magnetic fields play in accelerating cosmic rays?**<br><br>Reading: Choudhuri 10.5; |

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| | Notes: | Kulsrud 12.7<br><br>Notes: |
| **Week 13**<br>(April 20) | Topic: **What are the magnetic fields like around neutron stars?**<br><br>Reading: Choudhuri 13.7; Kulsrud 3.7<br><br>Notes: Problem Set #7 posted; Problem Set #6 due | Topic: **How do magnetic fields affect accretion flows?**<br><br>Reading: Choudhuri 5.7, 14.9.3; Kulsrud 7.4<br><br>Notes: |
| **Week 14**<br>(April 27) | Topic: **Are there magnetic fields around black holes?**<br><br>Reading: Bransgrove et al. *Magnetic Hair and Reconnection in Black Hole Magnetospheres* (2021)<br><br>Notes: Problem Set #8 posted; List of possible papers for the Final Exam posted; Problem Set #7 due | Topic: **How do magnetic fields affect turbulence?**<br><br>Reading: Choudhuri 8.1, 8.3, 8.6; Chapter 9.4 in Davidson *Turbulence: An Introduction for Scientists and Engineers* (2015)<br><br>Notes: |
| **Week 15**<br>(May 4) | Topic: **What are the ultimate origins of the Universe's magnetic fields?**<br><br>Reading: Introduction to Durrer & Neronov *Cosmological magnetic fields: their generation, evolution and observation* (2013); Section II of Vachaspati *Progress on cosmological magnetic fields* (2021)<br><br>Notes: Problem Set #8 due; last day of classes | **No class:** reading period |
| **Week 16**<br>(May 11) | **FINAL EXAMS**<br><br>Schedule Final Exam meeting via https://calendly.com/ryangolant | **FINAL EXAMS** |

## Class and University Policies:

Statement on Disability Accommodation: As a disabled person myself, I aim to be maximally accommodating to the needs of my students with disabilities. Please do not hesitate to reach out to me regarding disability accommodations – I am happy to schedule a one-on-one meeting early in the semester to discuss your needs. For additional assistance, you are encouraged to contact disability services (https://www.health.columbia.edu/services/ods) at 212-854-2388 and disability@columbia.edu. Please also be mindful of your student rights and responsibilities, as enumerated here: https://www.college.columbia.edu/rightsandresponsibilities.

Statement on Academic Integrity: While maintaining academic integrity and upholding the student honor code are both required of you as Columbia University students, they are also prerequisites for learning: any breach of academic integrity inevitably impairs your ability to achieve mastery of class material. As future scientists, . I encourage you to read the full Faculty Statement on Academic Integrity (https://www.college.columbia.edu/facultyadmin/academicintegrity) and to review the student's guide to academic integrity (https://www.cc-seas.columbia.edu/academic-integrity).

Class attendance policy: To the best of your ability, I expect you to show up for each class period on time; class attendance and punctuality will be factored into your course participation grade. If you anticipate missing a class, please let me know as early as you can; I am happy to help you catch up with missed material, either by connecting you with other students or by meeting with you individually. Similarly, if there is a recurring issue that causes you to regularly be late to or absent from class, please let me know as soon as possible so we can work out an accommodation.

Deadline policy: The deadlines in this course have been chosen to evenly distribute work throughout the semester and to ensure that each assignment builds upon the others; as such, it is in your best interest to complete work by the stated deadline. That said, I have no qualms granting extensions when needed, so please reach out as soon as you can if you anticipate needing to work past a deadline. However, do keep in mind that repeated extensions may cause work to pile up for you in the long run.

Technology policy: The use of technology is permitted in this course to the extent that it aids in your learning and does not distract others. Some in-class activities will require a laptop, a tablet, or a similar device with access to the internet; if this poses a problem for you, please let me know. The astronomy department has spare Macbooks for use if you are unable to bring a laptop to class; please let me know before class if you will be needing a laptop for that day.

AI policy: It is likely that ChatGPT or other generative AI tools will be able to solve many of the problems and parse many of the papers that we will tackle in this course. However, I guarantee that you will get more out of this course if you seek out other resources – like me (your instructor), your peers, your textbooks, and trusted online resources – before turning to AI. Furthermore, to the untrained eye, it can be difficult to recognize when AI provides you with an incorrect answer, as is often the case when ChatGPT tries to parse advanced scientific literature. Therefore, at least for this course, I strongly encourage you to resist the urge to use AI. If this poses any issues for you, please get in touch with me.

## Academic Support Services:

Snack & Solve: This is a program offered through Spectra (https://spectra.physics.columbia.edu/) that runs Wednesday nights 7:00pm - 9:00pm. At each Snack & Solve session, two physics TAs will be available to answer physics questions and to help connect you with other physics students. Pizza will be provided. While the material in this course may be beyond the expertise of some of the physics TAs, Snack & Solve is still a great environment for working together with your classmates.

Center for Student Advising (CSA) Tutoring Service: CSA can provide peer tutors for certain foundational mathematics and physics topics, listed here: https://www.cc-seas.columbia.edu/csa/tutoring. You can also contact physics administrative assistant Giuseppina Cambareri (gc2019@columbia.edu) to see a list of tutors available for hire within the physics department.

Paul's Online Math Notes: If you need a refresher on trigonometry, calculus, or differential equations, Paul's Online Math Notes (https://tutorial.math.lamar.edu/) are a fantastic resource.

Counseling & Psychological Services (CPS): If you are feeling overwhelmed and need help, please reach out to me, a friend, and/or CPS (https://www.health.columbia.edu/content/counseling-and-psychological-services) and make sure you are getting the support you need. You can call CPS at 212-854-2878. You can also attend a drop-in counseling session to receive spontaneous help from a CPS provider – for more details, see https://www.health.columbia.edu/content/problem-solving-drop.

Sexual Violence Response (SVR): SVR (https://www.health.columbia.edu/content/sexual-violence-response) offers trauma-informed confidential support and prevention programs focused on stopping gender- and power-based violence.

Nightline: Nightline (https://blogs.cuit.columbia.edu/nightline/) is an anonymous peer listening service, available via 212-854-7777.

## **Additional Resources**:

Astrobetter (https://www.astrobetter.com/): A blog covering anything related to professional development in astronomy.

Astrobites (https://astrobites.org/): Primarily a written astro-ph digest aimed at undergraduate astronomers. However, Astrobites also has tons of other resources for early-career astronomers; see Astrobites' "Beyond" posts and "Guides" for interesting and helpful advice.

Astro-ph (https://arxiv.org/archive/astro-ph): An archive of open-access astronomy papers, updated daily (except on weekends); a convenient resource for keeping up-to-date with astronomy literature (but be warned that not all the papers on astro-ph have been peer reviewed).

Astrophysics Data System (https://ui.adsabs.harvard.edu/): A powerful, comprehensive, and easy-to-use database of published astronomy papers.

Blueshift (https://blueshift.astro.columbia.edu/): Columbia's undergraduate astronomy club. Blueshift convenes once a month to discuss astronomy research and current events and to engage in other fun astronomy-related activities.

Columbia Astronomy Public Outreach (http://outreach.astro.columbia.edu/): Columbia Astronomy's outreach team organizes regular events to connect Columbia astronomers with members of the general public. Columbia Astro Outreach is a fantastic channel for applying your science communication skills in service of public astronomy education.

... and, of course, anyone in the Columbia astronomy department! Everyone in the department is friendly and more than happy to talk about anything astronomy-related, so always feel free to reach out to a department member directly or to ask me to connect you.