ASTR 501/701 Stellar & Exoplanet Atmospheres, Stellar Interior Structure & Evolution: spring 2017

TTh 14:00-15:15, Phillips 220

Instructor: Prof. Gerald Cecil, Phillips 272, cecil@unc.edu, office hr Th 15:30-16:30

1 Course Overview

This lecture/seminar examines the structure and evolution of stars from Main Sequence youth to death, as individuals and as a population. Earlier events, including the collapse of constituent gas clouds into accretion disks, are covered in other courses, as are rare relativistic end-products such as neutron stars and black holes whose study benefits from a course on general relativity. Thermonuclear fusion and atmospheric energy transfer bound stellar volumes; information from these regions comes to us directly as neutrinos and photons, respectively. The course will generalize power input and gas opacity sources to treat current exoplanet atmospheres illuminated and viewed from above, but heated both above and below. We do not consider planetary climate beyond discussion of radiative balance and simplified treatment of greenhouse gases, nor do we consider planetary interiors.

1.1 Required Co-requisites

PHYS 331 (numerical techniques) and PHYS 341 (thermal physics) are co-requisites, so the course is appropriate for physics BS juniors and seniors with developing computer skills. From thermal we use partition functions, chemical potentials (AKA Lagrange multipliers), detailed balance (AKA stochiometric) equations, Fermi degenerate gases, specific heats, entropy, various equations of state, and state diagrams.

As well as coding your own solutions, you will run and examine the output of stellar structure, evolution, simplified atmospheres, and population synthesis codes using modules of the comprehensive MESA package (`mesa.sourceforge.net`) installed on an 8-core blade of the UNC Linux cluster; run details are in §6.

1.2 Acquired Skills

You will come of feel accomplished in astrophysics by exploiting opportunities to apply and refine your growing knowledge of classical and statistical mechanics, E&M, QM, and relativity. In this course you will, among other things,

- learn physics of thermonuclear fusion processes and outcomes;
- model analytically and w/ computer codes radiative transfer through static atmospheres illuminated from below (stars) and above (exoplanets);
- model analytically and w/ computer codes the changes in stellar interior structure as a star evolves;
- enhance your python programming skills, e.g. numerical solution of coupled differential equations, use of Laplace and Fourier transforms, plotting of results, automated unit/error propagation. Please install the latest free academic Anaconda python installation (`store.continuum.io/cshop/academicanaconda`). You need a Mac, Windows or Linux laptop w/ python core + packages numpy, scipy, astropy, pandas, seaborn. Homework will only be accepted as jupyter notebooks uploaded to sakai. Necessary codes will be distributed from there. See Sakai Syllabus area for my python bootcamp document for details.

2 Assessment & Policies

Assessment: 1/5 of grade from each of

- Mid-term in early March. Make-up allowed only with MD permission slip.
- Quantitative computer homeworks generally assigned bi-weekly and due end of the following wk. Problems generally come as jupyter notebooks in which you develop a solution. Several are based on and translated from Mathematica codes in *Astrophysics Through Computation*, Koberlein & Meisel (2013) and python in Pierrehumbert's climate book (see below). All homework must track physical units using the python astropy.units package, properly reduced as we will discuss in class because an important part of learning astrophysics is to develop a feel for plausible magnitudes of results.
- Seminar leadership and participation (see below).
- Semester research project on some agreed-upon aspect of stars or exoplanets using the MESA simulation code. Expectations differ for A501/701.
- Final EXAM.

2.1 Late Policy

Unless you arrange with me before the due date or have an official University excused absence, you will lose 10% of total points daily for a late assignment.

2.2 Attendance Policy

I will provide lecture notes as PDFs ideally with audio commentary on sakai for you to review in detail before class. At some point in the semester the entire Thurs class will become a seminar, with students leading discussion of material. I will designate one of you to be the leader as we start. I will of course be present to prod, redirect, and enhance discussion as needed.

3 Required Textbooks

The textbooks below are available from Amazon and others either new or used, to buy or rent. Grad students in A701 should buy used copies for reference. From responses to my query in Dec. I learned that most of you want to concentrate on exoplanet atmospheres, the rest on stellar populations, after we have covered basics. Therefore, we'll do both but in seminars led by you so that all can learn by doing.

1. Stellar and exoplanet atmospheres. Required texts:

   (a) *Exoplanet Atmospheres: Physical Processes*, Seager 2010 (buy $37) [EA in schedule];

   (b) *Astronomical Spectroscopy: An Introduction to the Atomic and Molecular Physics of Astronomical Spectra*, Tennyson (2nd Ed.) 2011 [AS];

   (c) *Exoplanet Handbook*, Perryman 2014 (do not buy! pdf will be distributed) [EP].

   Useful/optional A701 references are *Radiative Transfer in Astrophysics*, Rutten (free online), *The Observation and Analysis of Stellar Photospheres*, (3rd Ed.) Gray 2010 (I will distribute copies of relevant parts from mine), and *Principles of Planetary Climate* by Pierrehumbert, 2010 (ditto). You learn how radiative processes diagnose physical conditions in the observed outer layers of stars and exoplanet atmospheres.

2. Stellar interior structure. Text: *An Introduction to Stellar Astrophysics* by F. LeBlanc, Wiley 2010 (rent this for $17, it is too basic to keep) [SA]. In this basic text you learn about the nuclear fusion cycles that power star luminosity and cook chemical elements. We consider the stellar life cycle from Main sequence to star death. Star birth is covered in Prof. Heitsch's course. Prof. Iliadis covers advanced nucleosynthesis.

3. Evolving stellar populations in galaxies, links to many topics in Prof. Kannappan's galaxy course. Text: *Evolution of Stars and Stellar Populations*, Salaris & Cassissi, 2005 ($48 used, buy this unique text/reference) [ES]. Follow star groups from their common birth and learn how to decompose galaxy starlight into these populations when the galaxy is too far away to measure individual stars.

4 Topics Covered and Tentative Schedule

Read [] prior to week of classes; explicit sections to work through will be assigned from sakai by Sunday each week along with PDF notes + accompanying ~ 45 min long audio commentary. The Tues lecture will review the highpoints of the recorded lectures, illustrate some calculations, and answer questions. In the Thurs seminar you will apply the material of that week to current research on stars, stellar populations, and exoplanet atmospheres. Keep up with the extensive reading, and start problems as assigned. There is much material to work through in this course, physics interspersed with numerical techniques and applications. The following list is illustrative, it will be revised.

Week of

1/17 [AS 1 & 2, EA 1 & 2, SA 1] Intensity, Flux, Black Body radiation, atmospheric temperature

1/24 Albedos, flux ratios, Boltzmann & Saha equations

1/31 [AS 5 & 6, EA 5, SA 3] Radiative transfer in stars and preliminary for exoplanets

1/31 [AS 3 & 4, EA 3 & 4] Review of atomic hydrogen, helium, alkali atoms

2/7 (I'm abroad this wk, so read on own [AS 3 & 4, EA 3 & 4] Review of atomic hydrogen, helium, alkali atoms)

2/41 [SA 4, EA 6] Solutions of radiative transfer

2/21 [AS 10, 11, 12, EA 8] Molecular spectra, greenhouse gases

2/28 [AS 13, EA 9, 10, 11] Vertical and thermal structure of planetary atmospheres, atmospheric circulation

3/7 [SA 5] Stellar interiors 3/14 Spring break, no classes. **Mid-term on atmospheres will be held near spring break.**

3/21 [ES 5, SA 6] H burning in core and shell

3/28 [ES 6] He burning

4/4 [ES 7] Advanced evolutionary phases

4/11 [ES 8] From theory to observations

4/18 [ES 9] Simple stellar populations

4/25 [ES 10] Composite & unresolved stellar populations, **MESA project due**

5/8, noon **FINAL EXAM**

5 Running MESA stellar structure solving code

While one can construct simple, inaccurate models of stellar structure at a given time with a few lines of python to call scipy ODE solvers, to really learn what is going on as a star evolves we need sophisticated code. Recently, stellar astrophysicists have standardized on a model suite called MESA. The code is well commented Fortran, worth a look, with modules to handle different stages of stellar evolution. You run it with input scripts, receiving tables and plotted outputs. To avoid installing all this on your laptop, I've customized a Ubuntu (Linux) image with the code and python installed. Login to `vcl.unc.edu` with your onyen then select from the list the image `[Cecil] MESA Ubuntu 14`. Off campus, you must be running the UNC VPN on your machine to get in and it will take up to 14 mins for the image to load; on campus it usually loads in 1 min. Once you have a Connect! button, click it. The popup msg will tell you the IP, say 152.19.198.92 On `MacOSX` start X (quartz, which you may have to install free from the Mac Store once), then in a terminal window type e.g. `ssh -X 152.19.198.92` and enter the login onyen and password given in the msg at the prompts. Then minimize the browser window. If you are running Windows, find and install the `putty` program, then under the Security tab checkbox X11 Port Forwarding and connect. In both, you'll be asked to affirm the ssh passkey at the first login, do so. Once logged onto the image, type source `/.bashrc` then `cp -r /opt/tutorial .` and then `cd tutorial` Read the REAME file in that directory. This headless server minimizes load time, so there is no desktop to display.

To compile the tutorial, type `./mk` and once it completes, type `./rn` to run it. As the run progresses, tables will flash by and 2 plots of the interior structure of the star will pop up, by default. The Ubuntu image cannot store results from run to run, so once you have output, on your machine e.g. `sftp 152.19.198.92` to retrieve it. You will also need to screencopy any displayed plots, although you can tell MESA to save them as png or pdf format files for retrieval too. Read the documentation on MESA in that subdirectory of our sakai site to learn how to change inputs and outputs.

When you are finished, maximize the vcl window and click Delete Reservation to free up that node. Be sure to get all your outputs from it first before it is wiped clean.