Introduction

Extragalactic astrophysics is a broad and rapidly evolving field. It sits at the intersection of cosmology, stellar astrophysics, stellar dynamics, and nuclear astrophysics. Much of our knowledge depends on empirical observation or detailed numerical modeling, rather than being derivable from first principles. These facts make good graduate textbooks in the field extremely difficult to write.

There is a great, broad textbook by Schneider that yields very complete coverage of the field; because it is a textbook it is not quite up to date, but it does contain all of the important topics. There are a number of text books of somewhat narrower focus that contain both fundamental astrophysics and thorough literature reviews (particularly Binney & Merrifield and Binney & Tremaine).

The approach of my text here is to use exercises to provide a practical introduction to the major aspects of theory and observation underlying extragalactic astrophysics. This yields not quite as broad a scope as Schneider, does not cover fundamentals as deeply as other texts, and of course is not quite at the frontier of the field. This text necessarily relies on reference to a broader set of books that provide a more complete background on physics and astrophysics. But it does deliver essential information on experimental techniques, analysis techniques, and particularly on phenomenology, that is hard to deliver in any other form.

Inspiration for this approach came from the *Problem Book in Relativity and Gravitation*. However, in extragalactic astrophysics the problems must include numerical and data-oriented questions to introduce the subject and to demonstrate its empirical and phenomenological aspects.

The topics that we are aiming to cover are:

1. Astronomical measurements of light.
2. The cosmological context for extragalactic observations.
3. Surveys of resolved stellar populations in the Local Group.
4. How stellar populations produce galaxy spectral energy distributions.
5. Galaxy redshift surveys, and galaxy properties and evolution.
6. Dynamics of stellar systems.
7. Baryon cycle in the interstellar medium of galaxies.
8. Measurements of galaxies from gravitational lensing.
9. Supermassive black holes and active galactic nuclei.
10. Galaxy formation theory.

The activities in *Exercises in Extragalactic Astrophysics* fall into three categories:

1. *Order-of-magnitude exercises*: These exercises are quantitative and meant to yield a sense of the units and quantities. They just require pencil and paper and usually no more information than is available in the material.

2. *Analytic exercises*: These exercises usually require physics and mathematics knowledge, in addition to the information available in the material. They just require pencil and paper.

3. *Numerics and Data Exercises*: These exercises require either minor computational work (computing integrals or derivatives) or minor analysis or plotting of astronomical data.

For the numerics and data exercises, in principle student can do these any way they want. However, we provide answers using Python, under Jupyter Notebooks. Some of the answers can be run on a laptop. Others need to use the SciServer Compute system. These solutions often take a pedagogical approach, which is usually less efficient than the approach one would take in a research problem. However, where convenient we illustrate the "professional" approach to solving the problem. Note that the convenience of Python and the professional approaches illustrated here will change over time, but hopefully the solutions will still yield insight.

For solving the numerical and data problems, some students may need extra introduction. In order of increasing sophistication we recommend the following resources:

- If you need to get your feet wet in Python without actually installing it on your laptop, go to SciServer Compute[1] and learn how to open a notebook and start a Python shell.

- Assuming you have some familiarity with some programming language, but perhaps don't know Python, the official Python tutorial[2] is as good a place to start as any.

- You need NumPy[3] and SciPy[4]. You may not want to go through all of those tutorials immediately but they are available if needed.

- You need AstroPy[5], which also has documentation and tutorials of use.

- Some of the answers as given rely on SciScript to access the SDSS CAS.[6]

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[1] `http://sciserver.org`

[2] `https://docs.python.org/3/tutorial/`

[3] `https://docs.scipy.org/doc/numpy-dev/user/quickstart.html`

[4] `https://docs.scipy.org/doc/scipy-0.18.1/reference/tutorial/index.html`

[5] `http://astropy.org`

[6] `https://github.com/sciserver/SciScript-Python`

- You may want to use Python on your laptop. Chances are it is installed with Python, but you will still want to use a distribution that you can customize without administrative privileges. Anaconda[7] is as good a distribution as any, and good for scientific use. You can use conda or pip to further customize it. To do this, if you are on Unix or Mac OS X but not familiar with the Unix shell, do consult the Unix shell tutorial at Software Carpentry[8].

The solutions in this book will provide some information on Python usage and capability. Note however that (at least partly by design for clarity) they are not always in the most "Pythonic" form or use the best software engineering practices.

There are a number of references in the notes to books and articles. In general, the articles can be found with a search of the Astrophysics Data System.

In the long term, the implementation used here will necessarily become dated as new observations and tools develop. I can only hope that it provides a useful set of exercises to students today and a durable model for future efforts in this direction.

[7]`https://www.continuum.io/`

[8]`https://software-carpentry.org/`