# Astrophysics Through Computation

with Mathematica Support

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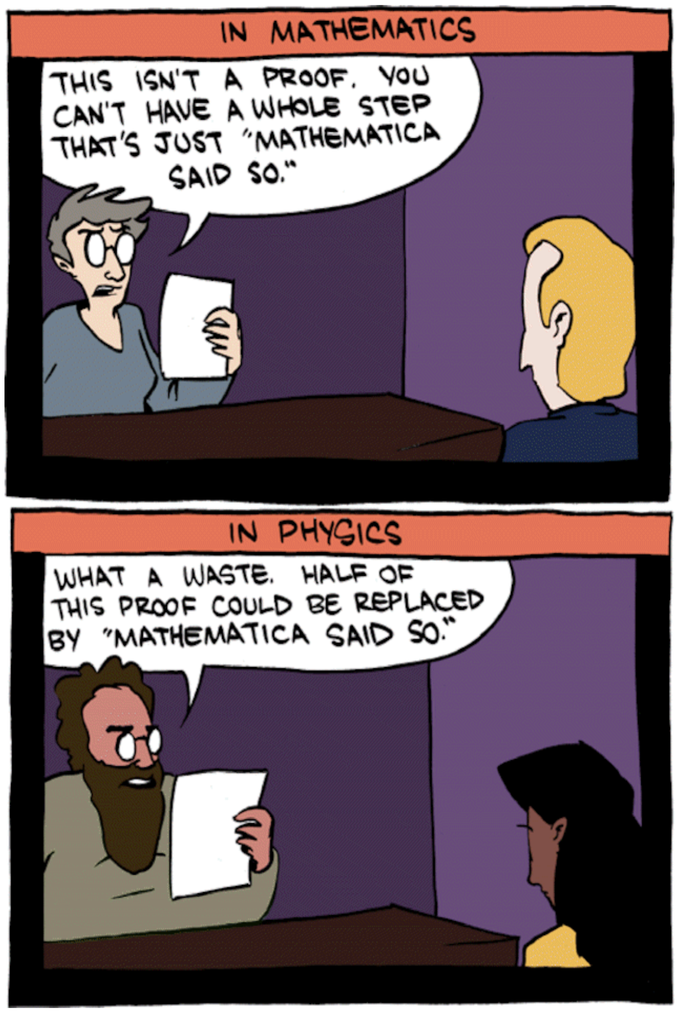

So why another book on astrophysics ? Undergraduates and first year graduate students are deluged with complex information that they are expected to “know” at least qualitatively. As a result there are plenty of texts that present just such a broad comprehensive survey of astronomy and astrophysics (either observationally or theoretically) and do that just fine. In fact there are many things being taught in introductory astronomy classes today that 50 years ago appeared only in doctoral theses. But in those same times, there were those (Chandrashekhar, Einstein, Hubble, and Spitzer for example) who having no access to the powerful computers of today developed the elegant analytical and observational theories upon which our modern ideas are based. Not only did these early people work with incomplete data sets and poorly understood physical concepts, they had to invent their own mathematical and computational methodologies to make their concepts quantitative. In contrast to today, the scientific progress of those times were largely products of sheer intellect from beginning to end.

Astronomy and astrophysics now make such immense strides almost continuously that undergraduate and beginning graduate students are rarely aware of the extraordinary quantitative foundations given to these disciplines during the 19th and 20th centuries and this knowledge gap widens with each passing day. There are two factors at work here. First the analytical mathematics used by these early masters was quite above that usually considered suitable for undergraduate instruction and secondly the actual computational programming required to produce realistic modern models these days is considered far too sophisticated to be meaningfully approached by all but the most advanced undergraduates and beginning graduate students. Yet NASA and other space agencies have often honored the intellectual giants of that era by naming spacecraft after them without explaining to modern students those lines of mathematical/quantitative reasoning that made the revolutions in thought of those scientists possible.

The purpose of this text is to use a modern computer mathematics system to give undergraduate and first year graduate students a quantitative bridge between the old and the new. We do not intend for this volume to be a comprehensive survey of astronomy and astrophysics (either observationally or theoretically). Instead we cover a series of topics where it is evident (at least to us) that the mathematical (analytical or numerical) development in the hands of a skilled “practitioner” was critical to understanding available observations and/or a proposed model. Our selected quantitative tasks had to fit the ready availability of the mathematical tools in the chosen computer math system and a number of topics were rejected as being unable to conveniently be solved because of an unreasonable amount of processing time, because the data were too big for a desktop computer, or because complexity issues obscured the concept we were trying to illustrate. As a result the level of presentation varies greatly with the difficulty of the problem. We do not avoid a discussion just because the concept is considered too difficult if the math can be used to produce intelligible results. In general, we do not expect students to write their own software from scratch but we do hope that they can use or notebooks as templates to their own applications.

If we do not include a favorite "moment in history" for every reader of the text, please consider those chosen as stepping stones to an extraordinary wealth of material from which you can formulate your own examples. In every case that we consider, we extend (and encourage the student to do likewise) the exploration of a cited early work by means of modern computer technology. This graphically (literally !) illustrates the quantitative directions that the work might have taken had such technological marvels been available in those early times. These computational activities also reveal various short comings in the early work that might been avoided had advanced computation been available. Students will learn to recognize these for themselves as they work thorough the text and notebooks. We do this so that students will develop a sense of connection between those days when most ideas started in the human brain and today's modern world of supercomputers where visualization is so complicated that the brain needs computer "filtering" to understand what the numerical results are saying. But just because we have tended to develop the ideas of astrophysicists of the past (and some of the present) does not mean we neglect to show some of the connections with the present and future.

To achieve our goals we have taken the broadest definition of computation possible to include data analysis as well as theoretical modeling as this is the way modern astrophysics has evolved. Scientific papers in all fields have become a synthesis of both theory and data analysis and today's students need to be able to navigate equally well in either capacity. Throughout the book we leave "nuggets" for future computational exploration with only brief comments about them, almost in passing. Only in the suggested computational projects do we make any reference to some of these. Instructors and students alike are expected to think about these on their own.

It may be wondered why we picked Mathematica for our programming system when others are readily available. One of us (DM) has used Mathematica as a programming system for the last decade and seen it evolve from a somewhat hard to learn and abstract mathematical programming language into a comprehensive mathematical analysis system that suits both theoretical development and extensive data analysis. Its coherent structure allows use for all research tasks without having to change software for different subtasks: (a) First it is practically the only system available that is transparently and completely cross platform. Secondly while other packages keep subdividing as new features are added, Mathematica gets more and more unified as befits modern research that is cross-disciplinary and interdisciplinary. The amount of scientific and computational capability in its current version is nothing short of spectacular as we illustrate in the over 115 notebooks we have used as the foundation of this book. Mathematica is now available internationally with versions that can be purchased directly by students and interested laypersons even if their home institutions have no licensed versions. There is also a free reader (Wolfram CDF Player) that allows anyone to at least read (and print) each notebook. If you want a taste of Mathematica at no cost then there is always WolframAlpha online as a massive public demonstration of Mathematica's capabilities. While only snippets of the needed Mathematica expressions at critical junctures are given in the textbook, the full notebooks with comments are available online. Because each of these is a self-contained "program" or collection of related algorithms, there are various levels of complexity involved in examining or running the contents there.

1) Beginner's level - At this level, of course, the best situation is to have a working copy of the regular, student or home Mathematica because in Version 8 there are several features that make learning the entire system so much easier than in the past including online direct connections to the Wolfram site and its new video tutorials for beginners or the availability of natural language commands like those in WolframAlpha. And of course having even the home or student versions give access to the full range of Mathematica capabilities for doing your own programming. But if full Mathematica capability is not available to a book owner Wolfram provides a way to examine a notebooks contents. Many of the graphic displays in the book are 2D projections of 3D rotatable plots and full access to this capability only requires getting a free copy of the Wolfram CDF Reader from the Wolfram website (http://www.wolfram.com). CDF Reader will easily read the many .nb files directly and allow native plot display and scrolling.

2) Intermediate level. - Running the notebooks or portions of notebooks with different data in "what-if-mode". Using some of the original Mathematica utilities provided in their own short programs or projects. If original routines or Wolfram owned routines are used in publicly available notebooks be sure to copy over the appropriate copyright notice into your own notebook. The regular, student, or home Mathematica is required for this.

3) Mastery level - Using these notebooks as templates for generating own versions or extensions of the full notebook for projects. Flow charts are recommended before starting drastic changes and always keep double copies of all modifications separate from the original notebooks as downloaded. The regular, student, or home Mathematica is required for this.

In the appendix we have also included a number of notebooks that are not officially part of the book but maybe useful for reference or use for readers of this text. These are in four areas:

a) coordinate transformations - astronomical coordinate systems

b) data processing - linear regression with errors in both variables

c) stats models - common distributions, random walks and Monte Carlo

d) thermonotebooks - support notebooks for a review of Statistical Thermodynamics. Includes an Excel spreadsheet for various stat thermo textbooks. Also a set of scanned passages that can be used with 2Entropy for comparison of English language information content.

As of version 9, there are also two items of special interest to first-time users of Mathematica included in this appendix:

One entitled Benchtest9 needs to be run (Selecting Evaluate Notebook from Evaluate menu will work just fine.) on the computer on which each person will be running these notebooks and/or developing their own. This is to aid an evaluation of how long it will take a given timed notebook or section to run on a particular computer and operating system. These notebooks were developed on a very fast machine that as of December 2012 scored 1.2 on this benchmark machine. How much longer or shorter a given segment can be determined approximately by taking a particular machine rating on this test and dividing it into 1.12 and then multiplying the result by the elapsed time given in the Mathematica listing.

The other item is directory/folder entitled "freeform". In both version 8 and version 9 of Mathematica direct links to the online service Wolfram/Alpha have been provided. These can be selected at any line which shows a "+" sign tab at the left side. Freeform input allows the use of "natural" language (in English) commands instead of regular Mathematica expressions. Clicking on the "plus" tab allows freeform either through special freeform notation or through direct Wolfram/Alpha connection.

We have tested some types of freeform requests and included these in a notebook called freeform/ V9Template.nb. The successful freeform commands are also listed in Alpha.rtf. To test the ability of the freeform commands to load local files is included. The test files for this are in the folder/directory "Put in user folder for V9" and must be placed in the default "user" folder or Mathematica will not be able to find them when running V9Template.

Finally we have resisted doing "fancy" programming in our notebooks, preferring to stay within products that an instructor is likely to see within their own classroom. These notebooks are not necessarily efficient or compact, but they do work well enough to get the point across. Our experience is that program authors are never satisfied with any of the versions they produce, but in this case we are. We are sure that talented student programmers can review these notebooks and produce better versions and they are welcome to try their hands at it. For them these notebooks should provide templates upon which more refined versions can be developed to their own personal tastes while they sharpen their programming abilities. Mathematica can be self-documenting within limits, but because of its built-in LaTeX word processing properties it has allowed us to provide much more documentation than a usual program listing contains. We have even provided some documentation to get students started in Mathematica programming using the subject of statistical thermodynamics as the background, but this book is not a programming manual as for that there are plenty of texts available. We have concentrated instead on computational matters of direct concern in astronomy and astrophysics.

**Important Note:** A certain number of the notebooks for each chapter require input files including databases that need to be present in the Mathematica default "user" folder (or directory depending on computer type, Mac PC, or Unix, etc.) in order to function properly when running in regular Mathematica. These must be placed in the proper place by the user BEFORE attempting to run the notebooks involved. Otherwise the notebooks are certain to malfunction. These essential input files appear in directories "putitno…" within each chapter. The way to identify the default location is obtained from the Mathematica documentation. In addition, in those chapters where extensive output files are produced by running the notebooks we have included the files produced by the notebooks.

**Bugs, Updates, and Upgrades**
These notebooks are constructed at a typical undergraduate student level and are not considered to be commercial grade programs. All have been tested using Mathematica V. 9 and found to be operable, but there is no guarantee that they will remain so given future operating system Mathematica version changes. If you wish to report a bug in the original notebooks (not modified ones, please), email the Author at ddmeisel@frontiernet.net with details.