Act III: Astrophysical Applications

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1. Introduction

I am fairly confident that by now, you are more than capable of setting up the essential conservation laws for a variety of astrophysical situations that you may encounter in your work, or in your leisure. You are prepared to handle gravitational fields (in the Newtonian Limit), electromagnetic fields (as MHD), and radiation (in a frequency-binned approximation). You also have the necessary references in the bibliography to strike out and address more complicated, and realistic, situations.

For that reason, in Act III, I discuss two types of problems where radiation plays a key role: winds/accretion and magnetoconvection, but I do not provide the *libretto* in these notes. Your single exercise is to write that *libretto*!

Historically, accretion came first owing to the widespread appreciation that stars must condense out of more tenuous distributions of material. The conversion of the gravitational potential energy of the infalling material to kinetic energy, and subsequently to thermal energy and then electromagnetic radiation which escapes the accretion flow, is a very nice demonstration of our methods in action. Hermann Bondi assembled all these ingredients in a seamless fashion, and Arthur Eddington pointed out that the force of the outflowing electromagnetic radiation on the infalling material could slow and possibly reverse the accretion process. Eugene Parker was the first to notice that the accretion energy conversion processes could work in the reverse order: excess thermal energy of a gravitationally bound gas could be converted into kinetic energy—without violating any laws of thermodynamics—which in turn could be stored as gravitational potential energy as a wind escapes from the gravitational potential well of a star. Radiation from the star can also help to lift the material out of the potential well.

Traditionally, these problems were addressed first under the simplifying assumption of spherical symmetry. This approach leaves out large-scale electromagnetic fields and rotation, both of which are usually essential ingredients in astrophysics. The references below discuss some of the two-dimensional axisymmetric treatements of these problems where these two agents come into play. Naturally these treatments are very much richer in complications and in the important astrophysical phenomena they describe. And, therefore, they are usually attacked by computational methods on very large computers.

I limit my remarks to the spherically-symmetric, analytically-tractable problems in the lecture. *You* should use all the spherical geometry equations I have been diligently supplying at the end of each of the Scenes, and try your hand at some axisymmetric problems!

Magnetoconvection, and magnetic dynamo theory, go hand in hand. And at a minimum they must be treated in three spatial dimensions to go beyond the most trivial concepts. They are also manifestly time-dependent. Here, too, one must firmly embrace numerical computer simulations of the the continuum RMHD equations and all that entails. It entails a lot, actually.

Computer simulations of RMHD viewed as *numerical experiments* is an exciting paradigm that is attracting considerable interest, and is stimulating tremendous progress. This *experimental* mindset implies that one very often runs simulations with parameters decidedly outside the bounds of our astrophysical expectations! This provides very valuable insights onto how complex processes interact by permitting the experimenter to dial-up or shut-off certain interactions through the assiduous choice of control parameters.

This paradigm should be contrasted with the more traditional *computational cinematography*, where the principal goal is now to massage numerical output to appear to match with one's preconceived notions of what some astrophysical system *should* look and behave like. This is perhaps not completely pointless, but, to paraphrase Eugene Wigner, there is a vast difference between the computer *knowing* the answer and the researcher knowing the answer. Indeed, here, when the goal is unachievable then we have actually learned something definite about what an astrophysical system is *not* doing.

In the lecture, *I* share some analyses of a numerical experiment on solar magnetoconvection, indicating by example, some ways to extract knowledge and understanding from huge arrays of numbers. *You* will probably spend some significant fraction of your careers constructing and/or experimenting with computational astrophysical simulations. Remember, as Richard Feynman cautioned, that you must *never* fool yourself in these endeavors, and unfortunately, *you* are the easiest person to fool.

The very best of luck and much success to you all in your future RMHD endeavors!

2. Exercises

Write the *libretto* for this Act of the *Opera*, and email me the document when you are done at tomjbogdan@gmail.com [Hint: Use the references below!]

3. Further Reading

A really nice all around treatment of stellar winds, and accretion, from a macroscopic viewpoint is

[**LC 1**] Henny J.G.L.M. Lamers & Joseph P. Casinelli, <u>Introduction to Stellar Winds</u>, (Cambridge, UK: Cambridge University Press; 1999), xiv+438.

For more extreme sorts of winds from compact objects, try

[**M 6**] F. Curtis Michel, <u>Theory of Neutron Star Magnetospheres</u>, (Chicago, IL: University of Chicago Press; 1991), xvi+517,

[**B 7**] V.S. Beskin, <u>MHD Flows in Compact Astrophysical Objects. Accretion, Winds and Jets</u>, (Berlin, DE: Springer; 2010), xvii+426.

For no particular reason, except it is a fascinating topic and one that is often glossed over, the astrophysics of binary objects is worthy of attention,

[**C 6**] C.G. Campbell, <u>Magnetohyrdodynamics in Binary Stars</u>, (Dordrecht, NL:

Kluwer Academic Publishers; 1997), xi+306.

*Un*steady winds and accretion, which in extreme cases are treated as blast waves, are handled very nicely by
[**K 3**] V.P. Korobeinikov, Problems of Point-Blast Theory, (New York, NY: American Institute of Physics; 1991), xii+382.
For much less mathematics and much more astrophysics, see
[**A 3**] David Arnett, Supernovae and Nucleosynthesis. An Investigation of the History of Matter, From the Big Bang to the Present, (Princeton, NJ: Princeton University Press; 1996), xviii+599.
And for much more variety and fascinating things you will not find elsewhere, don't miss
[**S 8**] K.P. Stanyukovich, Unsteady Motion of Continuous Media, (London, UK: Pergamon Press; 1960), xiii+745.

Between
[**G 5**] David F. Gray, The Observation and Analysis of Stellar Photospheres, 2nd Edn., (Cambridge, UK: Cambridge University Press; 1992), xvii+452,
[**PFL 1**] Kenneth J.H. Phillips, Uri Feldman & Enrico Landi, Ultraviolet and X-Ray Spectroscopy of the Solar Atmosphere, (Cambridge, UK: Cambridge University Press; 2008), x+349,
[**GP 1**] Leon Golub & Jay Pasachoff, The Solar Corona, (Cambridge, UK: Cambridge University Press; 1997), xiv+374,
you've got the whole optically-thin stellar atmosphere covered from end to end.

The only two things you are missing, from a radiative transfer perspective, are spectropolarimetry and molecules. For polarized radiative transfer, which is necessary to diagnose magnetic and electric fields in optically-thin plasmas, the "Bible" (both Old and New Testaments) is
[**DL 1**] Egidio Landi Degl'Innocenti & Marco Landolfi, Polarization in Spectral Lines, (Dordrecht, NL: Kluwer Academic Publishers; 2004), xvii+890.
Accept no substitutes! Get this book by whatever means and read it end to end. Period. Molecules play an increasingly important role in cool star atmospheres. They are present in the solar atmosphere. Although it is focused on the interstellar medium,
[**F 1**] David Flower, Molecular Collisions in the Interstellar Medium, (Cambridge, UK: Cambridge University Press; 1990), xii+133,
has a nice way of distilling the subject to some essential principles and rules of thumb. The concepts he presents are portable.

Weiss & Proctor [**WP 1**] provides a wonderful entry point to magnetoconvection in a variety of fluids. Magnetic dynamo theory, which is impossible to separate from magnetoconvection, is never-the-less often treated separately for a variety of reasons, many being historical. The astrophysical side of the subject is surveyed best by your own,
[**C 7**] Paul Charbonneau, Solar and Stellar Dynamos, (Berlin, DE: Springer; 2013), xv+237.

The mathematical side of the subject is very fascinating and centers on two dichotomies: fast versus slow dynamos, and local versus global dynamos. For a comprehensive discussion of the former, see

[**CG 2**] Stephen Childress & Andrew D. Gilbert, Stretch, Twist, Fold: The Fast Dynamo, (Berlin, DE: Springer; 1995), xi+406.

For the latter, start with

[**TCB 1**] Steven M. Tobias, Fausto Cattaneo & Stanislav Boldyrev, "MHD Dynamos and Turbulence", in P.A. Davidson, Y. Kaneda & K.R. Sreenivasan, eds., Ten Chapters on Turbulence, (Cambridge, UK: Cambridge University Press; 2012), pp. 351-404.