From Interacting Binaries to Exoplanets: Essential Modeling Tools
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Summary of Theoretical Techniques

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Abstract. In this summary, I address the next generation of theoretical tools with which it may be necessary to interpret the data anticipated as both stellar and planetary astronomy enter their next decades.

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One implicit theme of this meeting, bringing together as it does researchers in binary stars, stellar atmospheres, and planets, is that the field of exoplanets is reviving stellar astrophysics. Another is that the young field of exoplanets owes a great debt to the more mature and developed field of binary studies. Without an understanding of stars, we can't characterize the planets that orbit them. Without the tools developed by earlier generations of stellar astronomers, the field of exoplanets would be all but bereft of its modern methodologies. The manifest synergy between the two allied fields is something to exploit, and to celebrate.

The numerical tools crafted to understand binary stars and close-in planets orbiting their parent stars, their spectra, and their hydrodynamics require fast computers with large memories. It is curious to note that the pioneering early developments in efficient methodologies to study stellar atmospheres and interacting binary stars (e.g., Auer and Mihalas 1969 and Wilson and Devinney 1971, respectively) occurred ~40 years ago, just at the start of the ramp up in computational capability epitomized by Moore's Law. There has been a $\sim 10^5$-fold increase in the number of transistors per chip since that time and we as a field (or fields) are riding on the coattails of that dramatic exponentiation. Whether Moore's Law can continue through the next few decades is not clear, but what is clear is that progress at the cutting edge of planet and star theory will depend on continuing developments at the frontiers of computational science and applied mathematics. Moreover, there is little doubt that widespread access to increasingly-capable computers at competitive prices has been a key to progress across science, no less so in stellar and planetary astronomy.

I emphasize the importance of being at the cutting-edge of computation because the problems we have been pondering at this meeting, interacting stellar binaries and planet-star interactions, are fundamentally 3D radiation(spectral)-hydrodynamic problems (witness contact binaries and 3D general climate models!). Techniques for full non-LTE spectral synthesis in 1D stellar atmospheres are now at a high level of development. Techniques for 1D, 2D, and 3D hydrodynamics are as well. However, the coupling of the two, particularly when hundreds of thousands of transitions and rates are concerned, and in full 3D, has yet to be accomplished. The next-generation codes must include full time-dependence, most likely should include magnetic interactions, may have to include plasma processes, and most certainly need reliable spectroscopic and rate parameters and coefficients. The latter require complete databases validated by Laboratory Astrophysics, and the necessary compilation, archiving, and validation are by no means assured. Few scientists go into laboratory studies of processes of relevance to astronomers. Few chemists in the know about spectroscopy and chemical rates value the generation of databases that would be useful to astrophysics.

What is more, though atomic processes and spectroscopy have been the focus of astronmers for approximately one hundred years, and this focus has been necessary to elevate stellar atmospheres to its present sophistication, a corresponding effort has not been expended for molecular and exoplanetary atmospheres, their spectroscopy, or chemical rates. While there may be hundreds of thousands of transitions important for atoms, there are billions that are important for molecules. Thermochemical and spectroscopic data for molecules lag in quality far behind those available for atoms, except in temperature regimes of relevance to Earth's atmosphere. Even then, there are many holes in our chemical knowledge. What is worse, at the lower temperatures at which molecules form and come to dominate, clouds can form as well. Extant cloud models hardly deserve the name. Even for the Earth and its water clouds, we do not have a rigorous, predictive theory. Add to this, ammonia, silicate, and iron clouds, and hazes of currently indeterminate composition, and one glimpses the problems before us as we attempt to model, in credible fashion, cool planetary atmospheres.

A similar challenge confronts us as we seek to understand stellar evolution, a bullwark of binary and planetary studies. Almost all stars are convective and convection is a non-linear, 3D problem. Mixing and doubly-diffusive instabilities, convective overshoot into radiative zones, rotational dynamics, angular momentum transport, and magnetic field generation and influences (some pivotal) are all not only 3D processes, but occur on timescales much, much shorter than those of stellar evolution. This makes stellar evolution a numerically stiff 3D magneto-radiation-hydrodynamic problem, with 3D atmospheres (!).

However, the stellar evolution codes used in support of the science we have been discussing this week are one-dimensional, with ad hoc prescriptions to handle 3D effects. Mixing-length "theory" and 1D diffusion approximations to mixing processes are poor substitutes for the real multi-D dynamics executed by real stars. The upshot is that stellar evolution theory is not yet as robust as it needs to be to support star and planet studies that are achieving percent precisions. How stellar evolution theory will make its next leap is not at all clear, but make this leap it must.

With daunting radiation, hydrodynamic, plasma, chaotic dynamical, spectroscopic, atmospheric, and chemical challenges before us as we seek to improve the interpretative tools of exoplanet and stellar research, we must do more than passively ride Moore's Law to advance our science. We must inaugurate best practices in the computational arts, team with chemists and spectroscopists to create the most comprehensive databases of input physics, and foster a generation of theorists comfortable with and competent in computational astrophysics on its frontiers. The goal is a more comprehensive and credible theory of stars and planets as they execute their interactive dance, as well as insight into the distinctive characteristics that make planets planets.

References

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