Selected Research Accomplishments: Jonathan Dursi

Summary

In my recent work, I have:

- Examined cellular detonations in Type Ia supernovae, constraining the amount of partially-burned material that can be left behind;
- Calculated the response of flames to flow in Type Ia supernovae, with implications for turbulent burning speeds and flame instabilities;
- Shown that sufficiently strong magnetic fields in white dwarfs can entirely suppress flame instabilities, and that intermediate strength fields can cause flame-generated MHD turbulence;
- Found that modest amounts of Neon can change the ignition behaviour of Type Ia supernovae, and that detonations are very difficult to produce;
- Suggested that in galaxy clusters, pure hydrodynamics is very unlikely to be able to explain both the presence of persistent bubbles and AGN heating of the ICM;
- Examined a novel mechanism of 'dredge-up' in classical novae, found regions in which it can produce interesting results, and used these results as a subgrid-scale model in nova simulations;
- Helped develop the FLASH code, a major (∼450,000 lines of code) development effort towards a general-purpose astrophysical fluids code that won a Gordon Bell award for large-scale AMR computation;
- Shown that in many cases (where a significant fraction of the domain is refined), time-subcycling in AMR codes does not greatly enhance computational speed;
- Developed new techniques for accurately and stably computing phenomenon in nearly-static stratified atmospheres; and
- Rigorously compared simulations of astrophysically-relevant fluid instabilities to laboratory experiments, both increasing confidence in the results of the simulations and developing new understanding of the instabilities.

More detailed description of my recent work is contained in the following pages.

Type Ia Supernovae

Supernova of Type Ia are both fascinating phenomenon in and of themselves, and play an important role in cosmology. However, the underlying mechanism of these explosions remains something of a mystery, and scenarios previously considered 'exotic' may be required to explain recent observations. My past research on these objects has focused on understanding the ignition and burning microphysics that occurs in white dwarfs; this work is applicable to all plausible scenarios, and is aimed at creating microphysical inputs suitable for use in large-scale simulations.

Increasing scrutiny shows Type Ia aren't as uniform as previously thought. What's more, new observations suggest that there may be a 'prompt' population of Type Ia, which is very difficult to produce in the standard model of supernovae. Understanding these events requires better constraining the scenario which leads to explosion, and a more detailed understanding of the ignition and burning. However, critically examining both ignition/burning and the large scale mechanism simultaneously has been impossible, making distinguishing between scenarios difficult.

My most recent work on Type Ia supernova has focused on the small-scale physics of burning and ignition, with the goal of producing inputs to large-scale simulations. While the overall mechanism remains unclear, it is almost certain that the source of the explosion is the incineration of a carbon-oxygen white dwarf. Thus, questions of how burning would proceed in a degenerate mixture of carbon and oxygen are relevant to all Type Ia scenarios.

Early work of this type that I was involved with concerned the behaviour of detonations — supersonic combustion that propagates by shock heating. Real detonations are highly multidimensional structures, caused by a cellular instability that corrugates the front, greatly modifying the structure behind the detonation – in particular, leaving open the possibility of having some material only partially burned. This is of great interest for Type Ia supernovae because normally the existence of intermediate-mass (eg, only partially-burned) elements in the ejecta would disfavor detonations as an explosion mechanism; more detailed understanding of cellular structure allows us to better understand the constraints that observations place on detonation models. This work (Timmes et al., 2000) placed an upper limit on the density at which the cellular instability is likely to produce significant pockets of partially-burned material.

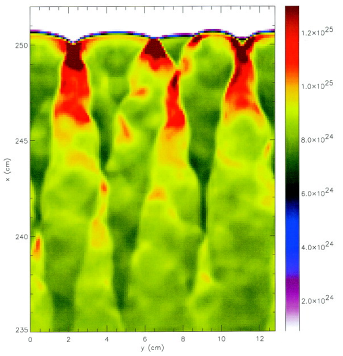

Figure 1: *Cellular Carbon Detonation, from Timmes et al. (2000).*

Although detonations may well plan a rule, most of the burning in Type Ia likely propagates as a flame; thus, the propagation of flames under degenerate conditions determines how these supernovae unfold. Flame instabilities are essential for speeding up burning, as corrugations in the flame increase the surface being burned at any given moment. Much of our understanding of these flame instabilities comes from the extensive work done in the terrestrial combustion community.

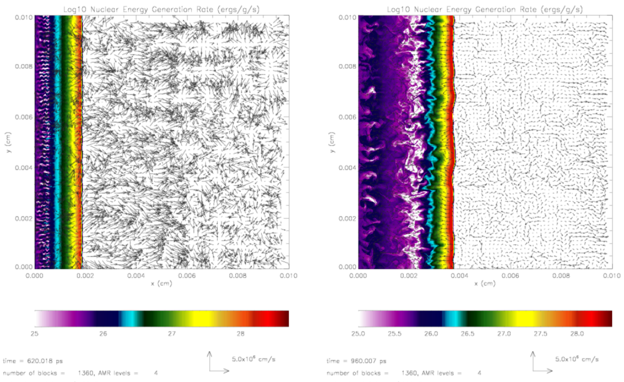

Figure 2: *Flame-turbulence interaction in Type Ia. Note that the flame suppresses small-scale wrinkling at the front, while material behind the front is greatly wrinkled.*

However, as we showed in Dursi et al. (2003), astrophysical flames in degenerate material have some different properties than terrestrial gas flames. Because of the electron degeneracy in a white dwarf, there is very little species diffusivity (compared to thermal conductivity). As a result, the flame reacts strongly to curvature; the modification due to changes in heat transport cannot be counteracted by fuel transport. One important consequence is that astrophysical flames are extremely stable to perturbations on scales less than about 50 flame thicknesses; a flame wrinkled on small scales tends to 'flattens out'. Even when the flame is unstable (or propagating through a turbulent medium), curvature can significantly reduce the local speed of burning in regions of high strain, and thus effect the total turbulent flame speed. This work also establishes the scales on which shear can effect local burning.

I have also examined the effect of magnetic fields on flame instabilities (Dursi, 2004). Magnetic fields can have only limited roles in terrestrial flames, where the relatively high magnetic resistivity mean that no local variations in magnetic field strengths can persist for dynamically interesting periods of time. For flames in astrophysical plasmas, however, a strong enough magnetic field – one for which the Alfvén speed exceeds the flame speed – can completely suppress flame instability. This can easily occur in X-ray bursts, but is less likely to play a global role in the evolution of a Type Ia supernovae. However, another interesting regime was uncovered in this work; when the flame is trans-Alfvénic, the flame becomes non-evolutionary (as is the case with trans-Alfvénic shocks), and flame-generated MHD turbulence becomes possible.

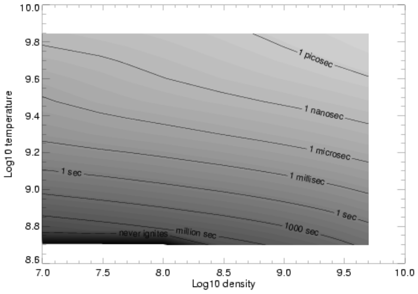

Figure 3: *Ignition times, from Dursi & Timmes (2005).*

Although much work has now gone into how burning propagates in a white dwarf, the question of how the burning ignites remains an open question – despite the fact that this is a necessary input to any model of a Type Ia, and that differing ignition geometries can strongly effect the final outcome of the explosion. Only recently has much work focused on ignition physics in a white dwarf.

In Dursi and Timmes (2005), we examined the one-zone ignition timescale for degenerate white dwarf material as temperature, density, and composition vary. This work was initially planned to be a useful but unremarkable tabulation of ignition times, which is a necessary step to more complicated models; however, we find something rather remarkable – even quite modest increases in the metallicity of the white dwarf, and in particular the Neon abundances, can significantly decrease the ignition time, significantly raising the probability of a hotspot ignition for more Neon-rich white dwarfs. This, as far as the authors are aware, is the first hint that there could be a difference in the ignition of younger white dwarfs than earlier.

We also examined the ignition of a detonation from a point, and find that a detonation requires much larger energy input – or coordination on much larger scales – to be successful than is generally understood. Detonations are extremely sensitive to curvature, and even modest curvatures make the propagation of a steady-state detonation impossible. This means detonations at interesting densities in a white dwarf likely require 'matchheads' of up to kilometers in size to launch a detonation.

Galaxy Clusters

The absence of catastrophic cooling in galaxy clusters has been partially explained by recent observations revealing X-ray emission voids of up to 30 kpc in size that have been identified with buoyant, magnetized bubbles injected into the intercluster medium by a central AGN. The mechanism by which these outflows heat the cluster medium as a whole remains unclear, but herein lies an opportunity; comparing the results of different heating mechanisms to the observed temperatures allows us to examine the outflow/ICM interactions, and thus to probe the ICM properties. In a recent work, we demonstrated that purely hydrodynamic flows are unlikely to be able to explain both the persistent bubbles and the AGN heating.

The presence of a surprising number of large 'bubbles', or X-ray emission voids, in the centers of large galaxy clusters is a bit of a mystery. On the one hand, it seems fairly clear that they represent regions of hot or magnetically-supported gas injected into the inter-cluster medium from an AGN in the central galaxy; on the other hand, their persistence (several being spotted at significant distance from the cluster centers) seems puzzling. This AGN heating is frequently cited as a method for heating the intercluster gas and preventing a cooling catastrophe; it isn't clear how this heating takes place if the hot material remains bottled up in an intact bubble.

Work done with an undergraduate research student K. Robinson at Chicago and P. Ricker at UIUC examined the simple hydrodynamic problem of a bubble in a stratified atmosphere (Robinson et al., 2004). Absent any physics which could constrain the hot gas, a bubble disrupts itself within a single bubble-height rise time, the vorticity induced in the fluid by the rising serving to shred the bubble. However, because of the presumably large density contrasts, even quite modest magnetic fields (eg, very small β) were enough to completely contain the bubble, which we showed through stability arguments of the Kelvin-Helmholtz instability and demonstrated using a small-β flux tube which could 'bounce' back and forth in the atmosphere quite undisturbed.

Although inconclusive – in particular, a simplified geometry was used for this work, and the bubble was an initial condition, rather being self-consistently inflated – this work suggested that it would be very difficult for purely hydrodynamic physics to agree with both the heating of the ICM and the presence of persistent large-scale bubbles; this point of view seems to be confirmed by more recent work.

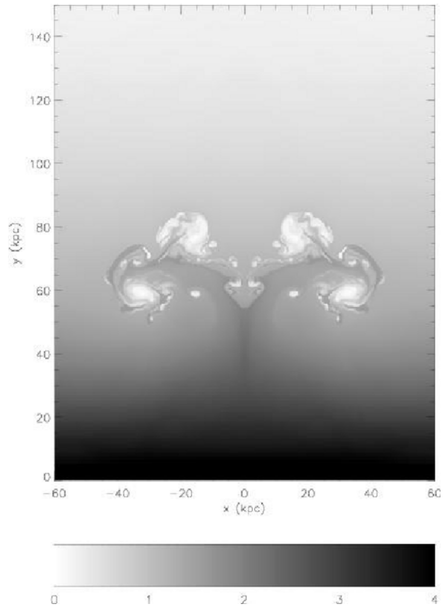

Figure 4: *A hydrodynamic bubble self-destructing, from Robinson et al (2004).*

Novae

Classical novae observations require material from the underlying white dwarf to be dredged up into the atmosphere; how the light envelope digs up much heavier white dwarf material is unclear. In one project, I have used simulations to test a novel mechanism – the resonant driving of gravity waves at the surface of the white dwarf by a wind, a mechanism responsible moisture in the air above lakes and oceans. There are regimes where this mechanism can produce interesting levels of mixing, and we have used this as a subgrid model in nova simulations. Techniques I plan on implementing over the next two years will allow considerable advances over current work.

Classical novae result from the accretion of material from a giant companion onto the surface of a white dwarf. The accretion continues until the base of the new atmosphere becomes hot enough that burning occurs, blowing off a great deal of the accreted material and its ash.

However, the abundances of the ejecta, and the energetics, imply that significant material is dredged up from the white dwarf itself and mixed into the atmosphere. This remains hard to explain ; it is difficult for light material to dig up heavier material.

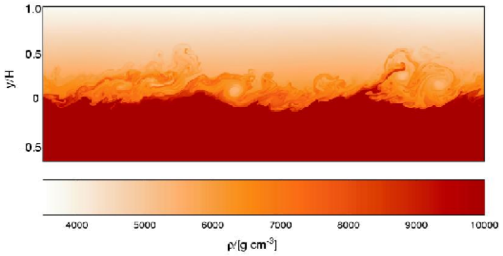

Figure 5: *Wind-driven mixing through the resonant driving of a gravity wave, from Alexakis et al (2004).*

One of my projects used simulations to test whether a new mechanism could be responsible for this dredge-up – the driving of winds on the surface of the white dwarf, which then break and mix material into the surface (Alexakis et al., 2004b,a). This mechanism is partly responsible for the mixing of water into air above bodies of water, where the density difference is much greater (about a factor of 1000) than in this case (about a factor of 10). Because of this similarity between an interesting astrophysical problem and terrestrial physics, this simulation effort garnered some press attention, including an article in USA Today and the prestigious "Surfing Journal". The results from an extensive parameter study were then used in global novae models to determine in what regimes this mechanism could contribute an interesting amount of carbon and oxygen to the atmosphere.

Computational Astrophysics

Doing new science sometimes means building your own equipment. I have been one of the developers of the FLASH code, a multi-physics, highly parallel, astrophysical fluids code that has won a Gordon Bell prize, and have published work on techniques on the efficiency of AMR codes and developing techniques for the smooth (transient-free) evolution of near-hydrostatic atmospheres using Godunov-type codes. I have also worked with experimental scientists in projects rigorously testing astrophysical codes, by verifying their solutions (ensuring that the correct solution to the PDEs is found) and validating them (comparing them directly to astrophysically-relevant experiments). Such work inevitably sheds as much light on the test problem as on the simulation codes.

My past work on computational techniques for astrophysics has focused on efficient large-scale parallelization of astrophysical codes; new methods for accurate hydrodynamical simulations; and testing those simulations by comparing to semi-analytical results and laboratory experiments. With the FLASH code, I have included improving performance of the already robust and efficient PARAMESH AMR package and the individual physics packages, helping FLASH win a Gordon Bell award (Calder et al., 2000), as well as increasing the accuracy of numerical techniques within the code.

Sometimes investigating efficiency of techniques leads to counter-intuitive results, such as our results in (Dursi and Zingale, 2003) which showed that one common technique, 'time subcycling', is of very little use in reducing CPU time in geometrically complex, explicit, AMR calculations. Time subcycling allows the use of fewer timesteps on coarse regions of the grid; however, except for special cases (including many cosmological simulations), these regions make up a small fraction of the zones. Reducing the amount of work on course zones, then, can have only very modest effect on total compute time, and only at the expense of significant algorithmic overhead.

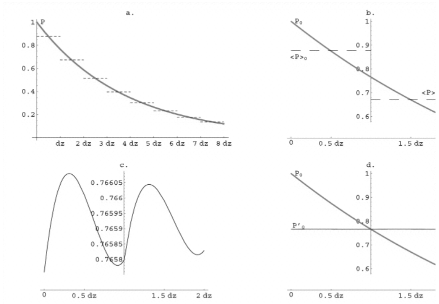

Figure 6: *Modifying the PPM reconstruction to take into account HSE; from Zingale et al (2002)*

For simulations to be useful, calculating them quickly isn't enough; they must also be accurate. With Mike Zingale and (then) undergraduate student John ZuHone, I have developed a set of techniques including modifications to the standard Gudonov-type hydrodynamics solver to increase the accuracy of simulations in stratified atmospheres (Zingale et al., 2002). We showed that this can make the difference between seeing real physics in the stratified atmosphere, or seeing only numerical transients caused by re-settling.

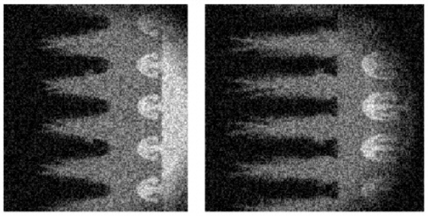

Figure 7: *Simulated radiographs for comparison to a laser experiment; from Calder et al (2002)*

Developing and improving numerical accuracy of an algorithm, however, is only the first level of building confidence in a simulation result. To make sure that simulations accurately reflect reality, contact must continually be made with experimental results. This is as true of established algorithms as they are applied to new problems as it is true of new hydrodynamic methods. I have been closely involved in the comparison of hydrodynamic simulations to laboratory experiments (Calder et al., 2002), and have been involved in the data analysis of one such experiment. This provides not only a way to test simulation codes, but to do new science. An excellent source of astrophysically-relevant laboratory test problems for codes are fluid instabilities. In this case, working with experimentalists not only provides challenging tests for a simulator, but can provide an opportunity to do real, detailed science on instabilities whose complex nonlinear evolution remains an unsolved problem.

An easier, but still valuable, test is to do code-code comparisons, to try to understand the uncertainties in numerical results that come from using different numerical methods (or different implementations of the same methods.) I was recently involved in a very large code comparison project (Dimonte et al., 2004) aimed both at understanding the nonlinear evolution of the Rayleigh-Taylor instability and understanding the differences in results between commonly-used codes by application to this problem.

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