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Magnetic Dynamos and Stars

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Abstract

'Djehuty' is a code that has been developed over the last five years by the Lawrence Livermore National Laboratory (LLNL), from earlier code designed for programmatic efforts. Operating in a massively parallel environment, Djehuty is able to model entire stars in 3D. The object of this proposal was to continue the effort to introduce magneto-hydrodynamics (MHD) into Djehuty, and investigate new classes of inherently 3D problems involving the structure, evolution and interaction of stars and planets.

However, towards the end of the second year we discovered an unexpected physical process of great importance in the evolution of stars. Consequently for the third year we changed direction and concentrated on this process rather than on magnetic fields.

Our new process was discovered while testing the code on red-giant stars, at the 'helium flash'. We found that a thin layer was regularly formed which contained a molecular-weight inversion, and which led therefore to Rayleigh-Taylor instability. This in turn led to some deeper-than-expected mixing, which has the property that (a) much ^{3}He is consumed, and (b) some ^{13}C is produced. These two properties are closely in accord with what has been observed over the last thirty years in red giants, whereas what was observed was largely in contradiction to what earlier theoretical models predicted. Thus our new 3D models with `Djehuty` explain a previously-unexplained problem of some thirty years' standing.

1. Introduction

Magnetic fields are ubiquitous in astrophysical objects, and many kinds of star show magnetic dynamo activity. Djehuty is designed to model entire stars in 3D, and operates in a massively parallel environment. Modeling in 3D is essential to study global processes like the redistribution of angular momentum in rotating stars, and the redistribution of nuclear composition by turbulent convection in deep interiors. It has the following properties:

(i) A grid which encompasses an entire star, from center to photosphere, with about $10^6 - 10^8$ mesh-points;
(ii) An equation of state that is realistic for stars, and adaptable for planets;
(iii) Opacities from the Opal library at LLNL for radiative heat diffusion;
(iv) It solves the Navier-Stokes equation for hydrodynamics, by a second order accurate explicit Lagrangian procedure;
(v) It solves the radiative transport equation in the 2-temperature diffusive approximation by an implicit procedure;
(vi) It contains an extensive set of nuclear reaction rates and reaction network;
(v) It solves for self-consistent gravity - at present, in the spherical approximation, but we are developing an implicit potential solver.

2. Stars And Magnetic Activity

It is probably a feature of all cool stars (and well-observed in the Sun) that there is differential rotation in the outer (convective) layers. Gas near the equator has an angular velocity substantially greater than the mean for the star as a whole. This excess angular velocity persists through the outer convection zone, and then abruptly disappears at its base (Schou et al 1999). This differential rotation (DR) is likely a consequence of the interaction between Coriolis force and turbulent motion of eddies that rise or fall in the convective outer layers. There have been attempts to model this in 3D, but cpu constraints normally limit such modeling to a sector, bounded by latitude, longitude and depth. It is not clear to what extent the model results are dependent on the boundary conditions that have to be imposed on the artificial boundaries. We can dispense with these boundaries, and study red subgiants or other cool stars.

DR is almost certainly the main cause of dynamo activity (Parker 1979). Most cool stars probably have a weak mean poloidal field, and the strong DR at the base of the surface convection zone means that at some latitudes the field is wound up into toroidal flux tubes. These flux tubes break away and rise to the surface through magnetic buoyancy. They are twisted and torn by the cyclonic turbulent convection as they rise. At the surface they emerge as starspot pairs, which then drift towards the poles, rotating slightly as they go (Wang 1998). The drift appears to be due to an azimuthal circulation current (ACC), which is presumably a consequence of the interaction of rotation with convection. As the pairs drift and tilt, they contribute a poloidal component, which can reinforce or oppose the mean poloidal field, establishing a dynamo cycle in which the field reverses every decade or so.

This proposal was to add magnetic fields to `Djehuty`, including force terms to the Navier-Stokes equation, and an induction equation. These are both major tasks. In addition it was necessary to develop the code's non-MHD capabilities, partly for validation and partly so as to be able to make comparison between magnetic and non-magnetic simulations. Of the poorly-understood phenomena in well-observed stars, a proportion are clearly magnetic in origin and a proportion are (less clearly) non-magnetic, but many (e.g. Be stars) are arguable either way and a comprehensive investigatory tool is needed.

A parallel development for `Djehuty` is to investigate tidal friction, a process which is certainly important in close binary stars and probably also important in close star-planet systems (Eggleton, Kiseleva & Hut 1998, Kiseleva & Eggleton 1999, Eggleton & Kiseleva-Eggleton 2001). A close companion raises tides, and one effect of convection is likely to be the dissipation (on a fairly long timescale) of the energy of tidal motion. This leads to corotation and circularisation of the orbit, but we wish to investigate the extent to which the DR and ACC driven by rotation and convection are modified by tidal dissipation. There is evidence (Hall et al 1995) to suggest that differential rotation is much less in tidally locked close binaries, but the magnetic activity is greater. We plan to investigate the influence of a close companion on the DR and ACC velocity fields of cool stars.

LLNL has a large body of scientists with expertise in magneto-hydrodynamics, planetary science, as well as high-energy-density physical phenomena appropriate to stars and giant planets. Several of these individuals have joined with us to extend the code. Omar Hurricane has made very significant contributions thus far for implementing MHD. In the following section we will describe the current progress in more detail.

3. Research Activities and Results

The 2004 schedule also included running Djehuty on non-magnetic problems to refine the general operations. Along this line, we have completed a number of simulations of a new supernova mechanism that has been proposed by Jim Wilson (LLNL) and Grant Mathews (Notre Dame), and a paper on the results has been published. In addition we began constructing models of binary systems with Keplerian disks, and the evolution of a Helium Flash star. This last effort addresses a poorly studied portion of stellar evolution through which most stars pass, and that requires 3D modeling. In this study we were joined by John Lattanzio, a professor at Monash University in Melbourne, Australia.

3.1. A New Supernova Mechanism

In 2004, we were pursuing two main topics: adding the magnetic force term to the hydrodynamics (HD) equations, and testing the HD part of the code, along with its capacity to compute binary stars, by simulating a new kind of supernova (SN) mechanism suggested by Dr J. R. Wilson (LLNL). Both goals were accomplished. The SN mechanism was published by Dearborn, Wilson & Mathews (2005). The mechanism is based on the fact that, when the proper General-Relativistic (GR) treatment of gravity is used, a star which is in a hyperbolic orbit around a black hole (such as the black hole at the center of our Galaxy) is subject to tidal compression that can increase the density on a short timescale and thus trigger an SN explosion. Without GR there is no net compression, although there will be density-preserving shear.

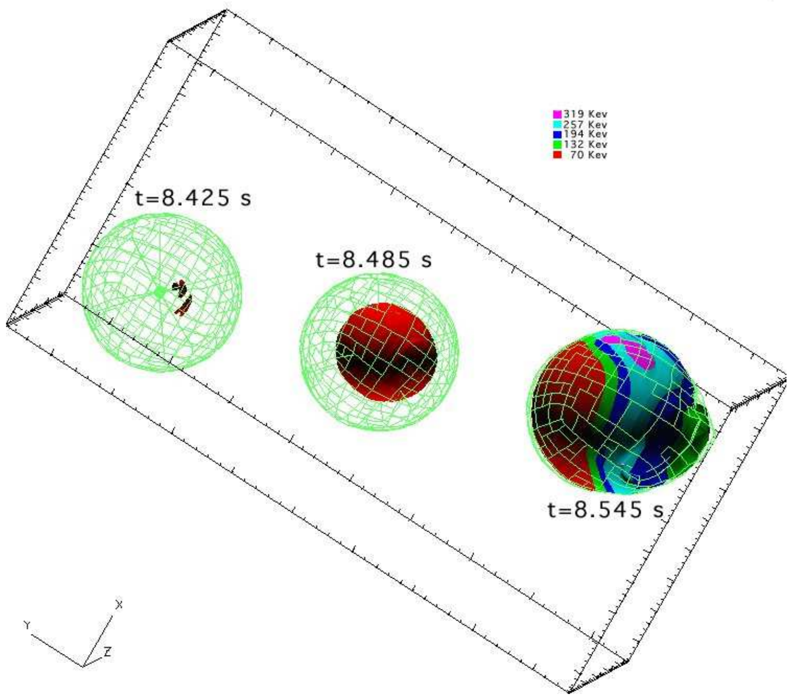

Fig. 1 – The progress of a supernova explosion in a white dwarf, as it passes near a massive black hole (well off the page). The explosion starts in the deep interior, when the temperature has reached about 70 KeV in the left-hand model. A hot bubble rises rapidly to the surface (right-hand model), containing material with temperatures above 319 KeV.

The development of the SN explosion is shown in Fig. 1. The Figure shows the white dwarf only; the black hole is several feet to the left on this scale. The explosion is seen to begin off-center, with small red patches of high temperature (measured in KeV). A hot bubble is formed which expands, and rises rapidly. In the third picture very hot gas is seen to have risen to the surface.

One important aspect of this kind of supernova is that it does *not* require a white dwarf which is massive, and close to the Chandrasekhar mass. Such white dwarfs, usually seen as the precursors of Type SNIa, are probably rare. But the new mechanism can ignite a supernova in a white dwarf of normal mass ($\sim 0.6\,M_{\odot}$), which is quite common. Of course it will not be very often that such a white dwarf approaches within 8×10^{12} cm of the Galactic center, as in Fig. 1. There is a SN remnant (Sgr A East) about $1'$ from the Galactic central black hole (Sgr A*), which we suggest could have been the result of such a flyby, although we cannot exclude the possibility of a more conventional SN explosion.

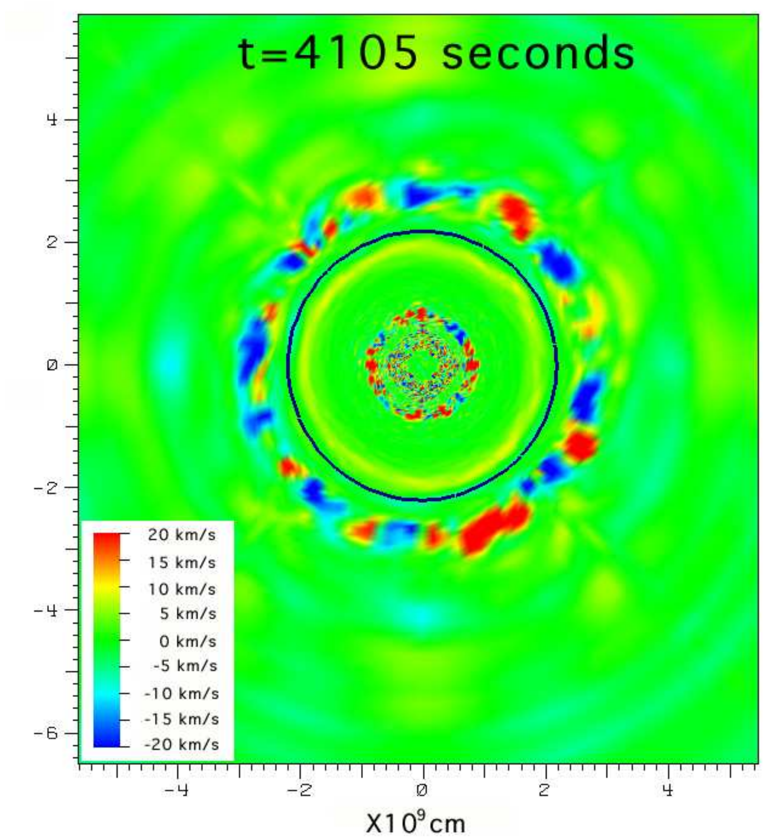

Fig. 2 – The deep interior of a red giant part-way through the helium core flash. The hydrogen-burning shell, which is the outer boundary of the helium core, is shown as a dark blue circle. Velocity is color-coded. Within the helium core is a region with a turbulent velocity field: convection driven by helium ignition.

3.2. The Helium Flash

Our major goal in 2005 was to model the helium core flash in low-mass red giant stars. We see this as an important test of the reliability of the code. The core flash begins when previously inert helium in the evolved core becomes compressed to a density of $\sim 10^6$ gm/cm^3, and heated to a temperature of $\sim 8 \times 10^6$ K

($\sim$ 0.6 KeV). Some estimates in the past have suggested that the ignition of the helium might lead to a violent explosion; although the normal expectation is that the explosion is rather mild, because many stars are seen which appear to be in a later stage of evolution.

We followed the evolution of a star, using a fairly conventional 1D (spherically symmetric) code, up to and indeed through the helium ignition. At several points in its evolution, after helium had begun to burn but before the burning peaked, we mapped the 1D model into the 3D code, and allowed the model to evolve. In all cases, after an initial transient during which convective motion was set up in the helium-burning region and the luminosity increased rapidly by a factor of 2 or 3, the 3D model settled to a relatively steady convection that was not radically different from the 1D model.

It has often been suggested that such models might be rather unstable, and that a random fluctuation in the burning rate might trigger a very asymmetric burn, whereas the 1D models are symmetric by definition. We tested this thoroughly, by imposing highly-localised high-temperature spots in the burning region, but always found that after the creation of a plume of hot gas the motion settled back to something that was quasi-steady. Thus we believe we can say with some confidence that helium ignition in electron-degenerate cores, while leading to a temporary runaway on a short timescale, is not inherently unstable, or explosive to anything like the extent that the ignition of carbon in degenerate cores is.

Fig. 2 shows the velocity (color-coded) on a cross-section through the central part of the computation region. The position of the thin hydrogen-burning shell is shown by a narrow dark blue circle. Within it is the core, of almost pure helium, and within that can be seen a region with substantial velocity in it (red or blue). This velocity field is the turbulent convection set up by the rapid burning of helium.

This work was published by Lattanzio et al (2004) and Dearborn et al. (2006a). We also considered the effect of rotation on the ignition of helium in such cores (Lattanzio et al 2006b).

3.3 Deep mixing in Red Giants

Our original intention was to continue the work of the previous section by introducing magnetic fields into the physics. However, an inspection of Fig. 2 showed us something unexpected, which we investigated and found to be very important. In Fig. 2, *outside* the dark blue circle, a shell of apparently turbulent motion is seen (also red or blue). We did not expect convective motion here, and so we investigated this region in some detail.

We found that the cause of the motion in this second shell was a small molecular-weight inversion, and that this inversion is caused by the burning of ^{3}He to ^{4}He plus ^{1}H. That this inversion exists is not some trick of 3D numerics, because when we looked for it in the 1D code we found it there. Any such inversion, in a fluid under gravity, should lead to Rayleigh-Taylor instability, and that is in fact the motion clearly seen.

This inversion does not exist only in red giants at the helium flash. Once we knew what to look for, we found it as we now expected in red giants that are still a long way from igniting helium. It is an inevitable consequence of the following interacting processes:

(i) A main-sequence star produces quite a lot of ^{3}He in its middle-to-outer layers. By the end of the main sequence the amount of ^{3}He in the star has increased by a factor of $30 - 100$, though it is still only a modest quantity ($\sim 0.1\%$) of all the material in the star.

(ii) When the star leaves the main sequence and becomes a giant, the whole of its outer region including the ^{3}He becomes convective, and is rapidly mixed to uniformity.

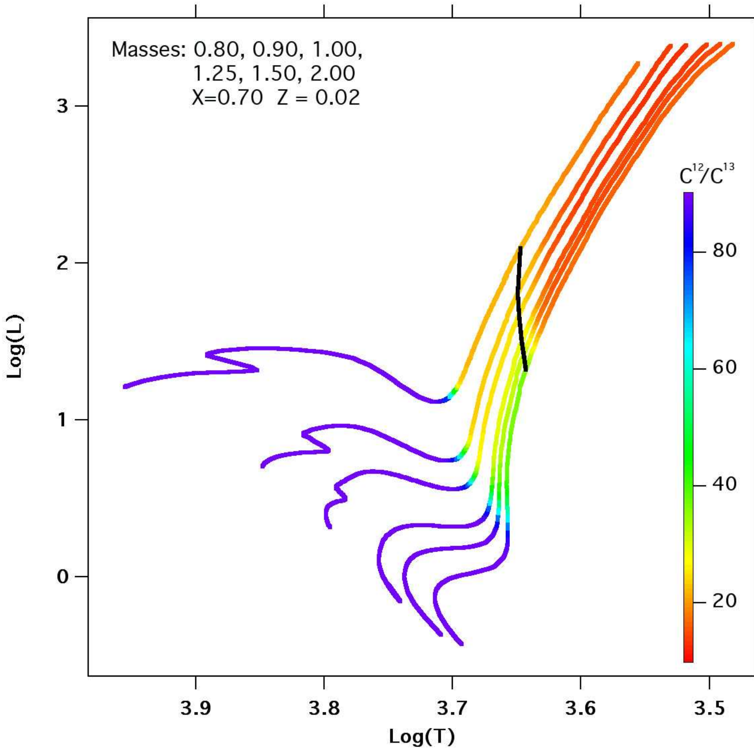

Fig. 3 – The decrease of the ^{12}C/^{13}C ratio with advancing age, for 6 stars with masses between 1 and 2 $M_\odot$.

(iii) The hydrogen-burning shell, which encloses $\sim 25\%$ of the star's mass when the deep surface convection zone is established, burns outwards, forcing the surface convection zone to retreat after it reaches some maximum depth; and as the convection retreats it leaves behind a region of *uniform* composition, relatively rich in ^{3}He.

(iv) As the H-burning shell advances into this uniform region, it is preceded by a small but significant ^{3}He-burning shell. This has very little effect on anything in the star, *except* for the fact that it produces a molecular-weight inversion, and this in turn produces Rayleigh-Taylor unstable motion.

(v) The ^{3}He-burning and the turbulent motion cannot extinguish the inversion, because the motion draws in fresh ^{3}He at the top at the same time that it burns it at the bottom.

(vi) The Rayleigh-Taylor motion is bound to extend in time right up to the normally-convective surface zone. Although the inversion is diluted by mixing it cannot be got rid of, and it is always replenished at its base.

(vii) This means that virtually all the ^{3}He in the surface layers is going to be consumed by burning near (but just outside) the hydrogen-burning shell.

(viii) At the same time, the moderately high temperature at the base of the ^{3}He-burning shell is enough to burn some ^{12}C to ^{13}C, and this ^{13}C will be mixed outwards all the way to the surface.

Our concept of Djehuty has always been that it can study hydrodynamic (and hydromagnetic) processes on a short timescale ($\sim 1\,\mathrm{hr}$, in Fig. 2), which can then be approximated by some simplified mathematical model inserted into a 1D code. We cannot follow a million years of evolution with Djehuty, but we can use the Djehuty results to embellish a 1D model which we can then follow for a million or a billion years. We have therefore incorporated into our 1D model a mathematical model of mixing driven by Rayleigh-Taylor instability. Some results are shown in Fig. 3.

In Fig. 3 are shown evolutionary tracks for a number of stars between 1 and $2\,M_\odot$. The tracks are color-coded according to the ratio of $^{12}C/^{13}C$: indigo is the primordial value (~ 90), and we see that the value decreases markedly as the star evolves up the giant branch. Without our destabilising molecular-weight gradient, the value would decrease only as far as the black line (where it reaches $\sim 20-30$), and would then continue at that value. But with our new mixing process included it continues to drop, to values like 10 or even somewhat less.

For some 30 years it has been known that stars on the giant branch contain more ^{13}C (Lambert & Dearborn 1972, Day et al. 1974, Dearborn et al. 1975, 1976, Tomkin et al. 1975, 1976, Tomkin & Lambert 1978, Harris & Lambert 1984a,b, Gilroy 1989) than can be accounted for by the 'canonical' models from 1D calculations. We believe we have solved this discrepancy. In addition, we have solved another discrepancy that is almost equally old. The canonical models would lead to a rather high concentration of ^{3}He in the Galaxy, because gas blown off by red-giant stars should have enriched the interstellar medium (ISM) in ^{3}He, probably by about a factor of 10 (Hata et al. 1995). Yet, although ^{3}He is a difficult isotope to measure, the evidence is that the present ^{3}He level is little different from what was expected in the Big Bang.

This work has been published by Eggleton et al (2006a, c), and two further papers are in preparation.

3.4 Magnetic Forces

One scheduled goal was simply to encode the MHD equations into Djehuty. Towards this goal, we explored a number of methods by which the magnetic force terms can be incorporated into the equations of motion, and the induction equation added to the system. To do this a 'mini-Djehuty' code was written to quickly test the accuracy and reliability of algorithms. This was done in the context of a number of initial possible field geometries including spheromak and dipole fields. The algorithms for initializing a field, evaluating the force terms, and including them into the equations of motion are already incorporated in Djehuty proper. We are currently working on the advection routines in Djehuty to assure that the Eulerian re-map operation, following the Lagrange step, conserves flux. When that is complete we expect to introduce the induction equation.

3.5 Accreting White Dwarf

To test the capacity of `Djehuty` to model complex binaries, we set up a calculation in which a low-mass main sequence star is transferring mass into the gravitational potential of a white dwarf companion. This was largely successful; but we moved our development effort to the mixing process described above.

3.6 Book; Tidal Friction; Multiplicity; Contact Binaries

PI Eggleton completed a book, now published (Eggleton 2006). Although this book covers a wide field (*'Evolutionary Processes in Binary and Multiple Stars'*) a significant part of it describes those evolutionary processes on which 3D calculations can be expected to cast significant light.

One of these is tidal friction, on which PI Eggleton has written extensively in pre-Djehuty terms (Eggleton et al. 1998, Kiseleva & Eggleton 1999, Eggleton & Kisseleva-Eggleton 2001, 2006). It was intended in 2006/7 to model this in 3D, using a $4\,M_\odot$ main sequence star with a (point-mass) companion as a test-bed. However, because of the extreme importance that we attached to the mixing process (Section 3.3) we have left this temporarily to one side.

When we have the opportunity to return to it, we expect the work to proceed in a similar way to that on the mixing proces. We should be able to follow the hydrodynamic evolution of the star subject to 3 or 4 eccentric orbits of the companion, and thus to estimate the rate of dissipation of the tidally-induced velocity field. An analytic treatment of this field has been investigated by PI Eggleton, and will be submitted for publication shortly. The 3D investigation should allow some very uncertain coefficients in the analytic model to be estimated much more realistically, and applied subsequently in 1D modeling.

Another topic discussed at length in the above book, and very suitable as a target for `Djehuty`, is contact binaries. A preliminary model has been set up on a 1D code, suitably modified. Its results are published by Yakut & Eggleton (2005). Because contact binaries have recently been identified with triple systems (Pribulla & Rucinski 2006) an investigation of the statistics of multiple systems seemed necessary (Eggleton et al. 2006).

4. Personnel

The core Djehuty group includes:

a) Peter Eggleton (who oversees code requirements, and testing). He has developed academic collaborations for binary star calculations and is leading the convective core study.

b) David Dearborn (who has written a number of code segments unique to astrophysical applications),

c) Don Dossa (the code manager, maintaining version control, documentation, and who enables its transition to new platforms),

d) Bob Palasek, taking over from Dossa as code manager.

The following are full time employees of LLNL who have had substantial participation in the development of Djehuty: Grant Bazan, John Castor, Kem Cook, Steve Murray, Pete Eltgroth, and Robert Cavallo (who recently took a permanent position in B Division). In 2005, Omar Hurricane was directly involved, providing experience in MHD.

5. Return To The Lab and Exit Strategy

The project aligns closely with DNT interests in numerical simulation as well as fundamental scientific research that supports stockpile assessment. It also connects the high high-energy-density Lab research done in PAT to the observed behavior of stars. The skills and interests of young scientists in stellar astrophysics overlap those desired in many LLNL programs, and B division has already recruited one of our post-docs. The Djehuty project will be the world leader in 3D simulation of stars, and has already attracted University collaboration with the possibility of recruitment. The projected code improvements are of direct interest to DNT Divisions, and will be transferred to programmatic codes. The end-product of this project is a computational tool of enormously wide application to astrophysical problems, thus aligning with the NNSA mission to support United States leadership in science and technology.

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