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The evolution and nucleosynthesis of low-mass stars

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The subject of low-mass stellar evolution and nucleosynthesis stands at the cusp of a revolution thanks to recent steps forward in several fields. In this review, I focus on three particular topics: asteroseismology, non-convective mixing on the giant branches and hydrodynamical simulations. Asteroseismology gives us, for the first time, a way of looking at what is happening in the deep interior of stars – regions that we have never before had access to. We are now beginning to appreciate the role that non-convective mechanisms (like rotation, thermohaline mixing and magnetic fields) play in the way material is moved around inside stars. Finally, hydrodynamical simulations have developed to the point where we can simulate significant portions of a stellar interior and watch how fluid motions transport chemical species. From this, we can hope to develop more realistic algorithms for the processes we wish to model in stellar evolution codes. Each of these fields is helping to push forward our understanding of stellar interiors and we can reasonably hope to see significant progress made in this field in the coming years.

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1. Introduction

The story of low-mass stars and their nucleosynthesis is really a tale of how material is transported around within a star. Unlike their high-mass cousins, low-mass stars never reach the higher temperatures required to activate the most advanced burning reactions. However, this does not prevent them having a rich nucleosynthetic life. Internal motion during the star's life allows materials to be exposed to both hydrogen and helium-burning reactions, one after the other, again and again. In this way, a low-mass star is able to form isotopes like ^{19}F and ^{23}Na. In addition, in the final phase of the life of a low-mass star, heavy isotopes beyond iron can be produce by neutron capture reactions. Once more, this process depends crucially on the transport of material.

The canonical picture (by which I mean that convection is the only means of transporting chemical species) of stellar evolution is as follows. Stars in the mass range 1-8 $M_\odot$ spend the bulk of their lives converting hydrogen into helium in their cores via either the pp-chains or the CNO-cycle. Once the core hydrogen is exhausted, the star swells up to become a red giant. It develops a deep convective envelope which eventually extends deep enough to draw CN-cycled material to the star's surface. This is first dredge-up (FDU). The ascent of the red giant branch (RGB) is terminated by the ignition of helium in the star's core, either quiescently in the case of the more massive stars or under degenerate conditions (the core helium flash) in stars below around 2 $M_\odot$. The star then contracts and settles on to the core helium burning phase. After the core helium is exhausted the star ascents the asymptotic giant branch (AGB), where the convective envelope once again deepens possibly resulting in another set of surface abunance changes (second dredge-up) if the star is massive enough. As the hydrogen and helium burning shells come closer together, the star enters the thermally pulsing phase. Recurrent episodes of runaway helium burning drive convective mixing between the two burning shells. Subsequent readjustment of the stellar structure allows the convective envelope to once again penetrate inwards, drawing freshly synthesised carbon to the stellar surface. This is third dredge-up (TDU). Eventually, strong stellar winds strip the star of its envelope, leaving behind a carbon-oxygen white dwarf.

We have known that the canonical picture is incomplete for some time. We know that there are non-convective processes at work that play a fundamental role in stellar nucleosynthesis. We see abundance changes on the upper parts of the giant branch that cannot be explained by convection (more on this later). To produce neutrons, we require diffusive mixing of protons into the carbon-rich intershell so that a pocket of carbon-13 can be formed. Understanding the origin of these transport mechanisms is the key to understanding low-mass stellar nucleosynthesis. For this review, I will discuss three topics that represent progress towards this goal, namely: asteroseismology, mixing on the giant branch and hydrodynamical simulations.

2. Asteroseismology

For most of the history of stellar astrophysics we have only been able to access information about the surface properties of stars. One could measure a star's brightness and surface temperature or if a star was in a binary system one could hope to infer its mass and perhaps work out its radius as well. Spectroscopy could tell us much about the chemical composition, but only of the surface layers. But the stellar theorist is really concerned with what goes on deep in the stellar interior – and up to now we have had no way of directly accessing these regions[1].

The discovery that the Sun oscillates with modes whose periods cluster around 5 minutes opened up the possibility of probing the Solar interior. Essentially, the convective motions of the Sun's envelope stochastically excite various modes of pulsation. Which modes are excited depends on the stellar structure, and so by studying stellar oscillations one can hope to probe stellar interiors. This has been used to great effect for the Sun. We know the depth of the Solar convection zone, we can infer the existence of the tachocline below the convective envelope, and we have a good handle on the Sun's (differential!) rotation profile. And this is all from studying *surface* properties!

The same techniques have now been applied to more distant stars and the results are encouraging (and in some cases, astonishing!). Obviously, we cannot hope to get such detailed information as we can for the Sun as we cannot image a star's surface to the same level of detail. This means we will not have access to the high-order modes of oscillation and the information they contain. Typically one can only get hold of the lowest order modes up to about $l = 3$ [9], but this is enough to uncover some valuable information.

In the last year, the field of asteroseismology has come on in leaps and bounds. This is particularly due to dedicated space-based mission like CoRoT [4] and Kepler [16]. I shall focus in particular on the Kepler mission because many interesting results have recently come from this mission[2]. The Kepler mission, launched in March 2009 and initially given a mission length of 3.5 years, is currently monitoring 100,000 stars in the regions of Cygnus and Lyra.

The results have been little less than astonishing. First, I will discuss the case of the work of Bedding et al. [6]. After ascending the giant branch, a low-mass star undergoes helium burning and can settle down to the red clump. During this phase of evolution the star has a surface temperature and luminosity that are indistinguishable from a star going up the giant branch for the first time. On the Hertzsprung-Russell diagram we cannot separate the two groups. For fields stars, where the initial chemical composition of a given star is unknown, we cannot use surface abundances to determine which stars are which. But asteroseismology can tell the two groups apart. Ordinarily, g-mode pulsations[3] are extremely weak at the stellar surface so as to remain undetectable and we only observe p-modes. P-modes do not propagate deeply into the star and so do not provide us with information about the innermost stellar regions. However, in red giant structures, g-modes in the stellar core are able to couple to p-modes in the stellar envelope. With this coupling, we obtain information about the stellar interior.

The work of Bedding et al. [6] shows the power spectra of two giants observed by Kepler, namely KIC 6779699 and KIC 4902641 (their Fig. 2). The former is undergoing shell hydrogen burning on the giant branch while the latter has settled down to core helium burning. The $l = 1$ modes exhibit noticeably different structures, enabling us to differentiate between the two struc-

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[1] In the special case of the Sun, the study of solar neutrinos and their energies can tell us about the nuclear reactions taking place.

[2] The author cannot resist taking a sideswipe at NASA over the mission's website. Go and look at it, and you will fail to find *any* mention of asteroseismology, as it exclusively talks about planets. Shame on you, NASA, for hiding all the great science that is being done on stars!

[3] These are pulsational modes where gravity supplies the restoring force. P-modes are acoustic modes where the restoring force is pressue.

tures. Furthermore, [6] also shows that if one plots the average period spacing of the observed modes against the large frequency separation then the core helium burning stars can clearly be separated from those stars still on the giant branch, with the former having period spacings of between 100 and 300s and the latter having period spacings of around 50s.

The same coupling of modes also opens up other avenues for probing stellar interiors for giant stars. Beck et al. [5] report the detection of $l = 1$ modes with distinct splitting in three stars in the Kepler field. This splitting is consistent with stellar rotation, which is expected to raise the degeneracy of the non-radial modes, producing $2l + 1$ multiplets. These authors compare the observed splitting of the $l = 1$ modes for KIC 8366239 to the splitting predicted by two different rotational laws (see Figure 1 in [5]). The splitting predicted by a model which assumes solid-body rotation with an equatorial surface velocity of 3 km/s is clearly inconsistent with the data. In contrast, a model in which the core rotates ten times faster than the surface shows much better qualitative agreement with the data. In principle, this means we should finally be able to constrain the rotational profiles (and by extension the rotational physics) of giant stars.

These results (and others, see the contribution by Pinsonneault in these proceedings) are extremely promising. For the first time we are obtaining direct information on the structure of stellar interiors. Stellar modellers now have something to directly compare to their computations of stellar interiors, rather than having to rely on the effects of non-convective processes on surface properties such as chemical compositions.

3. Mixing on the giant branch

Non-convective mixing plays an important role in stellar nucleosynthesis. The phase of evolution where this is most obvious is as the star evolves towards the tip of the red giant branch. According to canonical stellar evolution theory (i.e. where convection is the only process able to transport material), the only place where the surface abundances of a low-mass star change is as the star becomes a red giant. At this point, the convective envelop deepens, reaching into regions where CN-cycling has occurred. This leads to a drop in ^{12}C at the stellar surface, while both ^{13}C and ^{14}N increase. This is first dredge-up (FDU). From the end of first dredge-up to the tip of the red giant branch, no further abundances changes are predicted. However, this is not what is observed!

The deepening of the convective envelope leaves behind a discontinuity in the hydrogen abundance. When the hydrogen burning shell reaches this discontinuity, the star undergoes a structural readjustment and its luminosity drops slightly before recovering again. In clusters, this leads to an enhanced number of stars being seen at this point and it is referred to as the luminosity bump. Above this bump, surface abundance changes are seen to occur. Gratton et al. [13] observed depletions of lithium and carbon, while the ^{12}C/^{13}C ratio was also seen to drop. At the same time, the nitrogen abundance increases. Oxygen and sodium do not seem to be affected by whatever process is at work. These abundance changes seem ubiquitous: they are seen in globular clusters and in field stars. They occur at all metallicites, with the changes being more extreme at lower metallicity.

Much work has been done on trying to determine the cause of these changes and it is impossible to list all the contributions in this review. Instead, I will focus on one recent development that initially seemed quite promising but has since run into difficulties. While working on three-dimensional hydrodynamics models of red giant structure, Eggleton, Dearborn and Lattanzio

[12] noticed unexpected fluid motions just above the hydrogen burning shell in their model. They tracked the origins of this motion to a reduction in the mean molecular weight of material in this region. The mean molecular weight drops because of a peculiarity of the reaction ^{3}He(^{3}He, 2p)^{4}He: it produces more particles than it uses up. Having material of higher mean molecular weight on top of material of lower mean molecular weight is secularly unstable, resulting in fluid motions and mixing. This kind of mixing is well-known in oceanographic circles, where it is referred to as thermohaline mixing. It is a doubly-diffusive process that depends on there being a difference in the diffusivities of the stabilising (heat) and destabilising (salt, or composition in the stellar case) agents.

Using a diffusive prescription for this process, Charbonnel & Zahn [8] showed that the operation of thermohaline mixing could indeed account for the observed abundance changes on the red giant branch. They also showed that thermohaline mixing led to more pronounced surface abundance changes at lower metallicity, in agreement with observations. Subsequently, it was shown that the same prescription with the same choice of free parameter also matches the observed behaviour of low-mass stars in globular clusters [2] and accounts for the different behaviour of metal-poor carbon-rich and carbon-normal stars [23]. At the time, it seemed like we had finally got to the bottom of the mystery of abundance changes on the giant branch.

As with all things, the devil is in the detail. If one looks into the derivation for the diffusion coefficient for thermohaline mixing, such as that given by Ulrich [27], one sees that the free parameter which the modellers fit to reproduce the observations relates to the geometry of the mixing. Mixing is assumed to take place via the form of salt fingers and it is the aspect ratio of these fingers that determines the rate of mixing. One would hope that if we were to simulate thermohaline mixing using hydrodynamical codes then the geometry of the fingers found in these simulations would match the value required by stellar modellers. Sadly, this is not the case. Hydrodynamical simulations of thermohaline mixing have recently been performed by Traxler, Garaud & Stellmach [26] and Denissnekov & Merryfield [11]. Both groups agree that the transport properties of their simulations are far too small to agree with the large diffusion coefficients that observations seem to require.

As if this failure to understand abundance changes on the giant branch was not disturbing enough, there are hints that further problems may await us. Johnson and Pilachowski [15] have presented evidence for severe oxygen depletion towards the tip of the giant branch for stars in the globular cluster M13. This would be impossible to reconcile with thermohaline mixing (even if the hydrodynamics did support the high diffusions coefficients being used by stellar modellers), because the mean molecular weigh inversion required to drive thermohaline mixing occurs at temperatures too low to allow for ON-cycling. M13 is not the only globular cluster that may cause us headaches. Recent work by Angelou et al. [1] (see also the contribution by Angelou et al. in this volume) has shown that in M15 the surface carbon abundance changes substantially *before* the end of first dredge-up (and worse, it may even increase again very close to the tip of the giant branch). While the data used is inhomogenous, if this result is true it represents a substantial challenge to stellar evolution theory. It seems we have not yet got to the bottom of non-convective mixing on the red giant branch!

4. Hydrodynamical simulations

To finish off this review, I wish to discuss what I believe is currently the best hope for advancements in the field of stellar interiors. Computer power has now advanced to the point that it is possible to do simulations of the fluid processes that occur inside stars. Hydrodynamical simulations are the theorist's equivalent of laboratory experiments. They allow us to take the structure of a star from one dimensional calculations and see what is happening with regards to the fluid flow. We are therefore able to look at how material is mixed into convection zones, how the boundaries of convective zones behave and what mixing processes may be active in non-convective regions. They have the power to point to processes that may not have already been considered in stellar evolution calculations, as we have already seen in the case of thermohaline mixing [12]. However, for the foreseeable future, they cannot tell us about the long-term evolution of stars: at best hydrodynamical simulations can be run for a handful of hours of stellar time, at the expense of hundreds of thousands of hours of CPU time.

Many groups have been active in employing hydrodynamical simulations to various stages of stellar evolution. The following list is not intended to be complete, but should hopefully give some idea of the work that is currently in progress. Meakin and Arnett have been studying convection in massive stars in both 2- and 3-dimensions [18, 3]. They have been working with the aim of providing an improved prescription for convection for use in 1D stellar evolution codes (the so-called 321D approach). For low-mass stars, Mocák and collaborators have looked at various aspects of the core-helium flash [21, 20]. Their work has shown that turbulent entrainment of material at the outer edge of the convection zone leads to the zone growing on a dynamical timescale. In addition, their work has also demonstrated that there may be some kind of non-convective mixing process at work at the base of this convection zone [19]. Eggleton and collaborators have employed the Lawrence Livermore hydrodynamic code DJEHUTY to a variety of evolutionary phases including the core helium flash [10], as well as discovering the role played by ^{3}He burning in red giants, as described above [12].

One area that I have been actively involved in is the application of hydrodynamical modelling to the so-called proton ingestion episodes (PIEs) in low-mass low-metallicity stars. In these events, a convective region being driven by helium burning is able to penetrate through the hydrogen burning shell into proton rich regions. These can happen both during the core helium flash at the tip of the RGB and also in the early thermal pulses on the AGB. Once the protons are ingested into the helium-driven convective zone they are pulled down to extremely high temperatures where they burn vigorously. In the 1D stellar evolution models this can lead to the convective zone splitting into two. The high energy release from proton-burning drives an upper convection zone while the lower zone continues to be driven by helium burning[4]. This finding seems to be almost ubiquitous amongst stellar evolution codes, e.g. [14, 25, 17, 7].

The situation experienced in PIEs is unusual for stellar evolution. The timescale for nuclear burning and mixing is comparable (and presumably structural changes may happen on a similar timescale as well), and we should pay particular attention to whether we are doing the mixing correctly. In many stellar evolution codes mixing is modelled via a diffusion equation, with the

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[4] A similar situation exists in stars undergoing a very late thermal pulse whilst on the white dwarf cooling track. Hydrodynamical simulations for this phase of evolution have been carried out by [14].

diffusion coefficient being derived from the mixing length and the velocity as derived from mixing length theory. Given the limitations of mixing length theory, we may maintain a certain skepticism as to whether our 1D computations are correct. Fortunately, this is where hydrodynamical simulations come to our aid.

We have simulated a $1\,M_\odot$ star of $Z=10^{-4}$ undergoing a proton ingestion episode using the stellar hydrodynamics code DJEHUTY [22]. The 1D input model was taken from an evolutionary sequence made using the STARS stellar evolution code [24]. DJEHUTY allows us to simulate a full sphere of the stellar interior, covering the whole of the intershell convection zone out to just below the convective envelope. The simulation was run for over 4 hours of stellar time, which is roughly four times the convective turnover time predicted by mixing length theory.

In agreement with previous simulations of convection (e.g. [14]), we found that the convective flows could be divided up into fast-flowing, narrow downward plumes and broad, slow-moving upflows. The average speed of these flows was found to be at least an order of magnitude faster than the predictions for mixing length theory. More importantly, the peak downflow speed could reach over 100 km/s. At this speed, it only takes a few hundred seconds to cross the entire intershell and this is much shorter than the proton-burning timescale. This means that protons do not burn in flight: they are transported all the way down to the base of the convective zone and they are only consumed when they reach it. This means the extra energy from proton burning is being added into (roughly) the same region as the energy from helium burning, with the consequence that *the convective zone can never split into two*. Obviously this is at odds with the predictions from 1D stellar evolution codes![5]

This case illustrates the role that hydrodynamical simulations can play in aiding stellar theorists. We have modelled a situation where we have good reason to believe are 1D models are not correct. The results of the simulations provide both a confirmation that our model is failing and by studying them we can hope to come up with a better treatment of the physics of this process. One wonders what other applications hydrodynamical simulations could be used for? For example, could simulations of the base of the convective envelope of an AGB star allow us to finally determine what the mechanism for the formation of a ^{13}C pocket is? If so, we may finally arrive at a full understanding of the *s*-process!

5. Summary

In conclusion, I would like to re-iterate my belief that it is an exciting time for working on low-mass stars. The confluence of several areas of stellar astrophysics opens up the potential for making great progress (one hesitates to say ‘revolution’ but time may show that this is appropriate) in our understanding of stellar interiors and their nucleosynthesis. The success of missions like Kepler means that asteroseismology is beginning to give us direct access to what is going on in the deep interiors of stars. This opens up the possibility of constraining models for e.g. stellar rotation. The advent of hydrodynamical models of stellar interiors allows us to test the assumptions used in 1D evolution codes, helps us to improve the models of transport processes in those codes and has the potential to show us new processes we have not thought to include in the past. It is my firm

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[5] There may also be problems with maintaining the stability of such a two-zone configuration in 3D hydrodynamical simulations. See [20] and also Heap et al. in this volume.

believe that these new developments may finally help us crack some of the remaining problems in this field.

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6. Questions

Comment from Maurizio Busso: *As you showed, the mixing “free” parameter of any diffusion treatment of mixing must be very large (c≈1000). This goes to the same direction as hydro codes, in telling us that thermohaline diffusion is NOT a suitable mechanism. The Delta Mu generated by* ^{3}*He burning is too small, and the mixing speed is too slow. Magneto hydrodynamical instabilities have instead been shown to have the lowest properties.*

Response: Thermohaline mixing is certainly not without its problems, but I am loathe to discard it too readily. It has the virtue of matching the observations in a variety of situations with the use of the *same* free parameter. In this sense, it is no different from Mixing Length Theory (MLT): we fix a value for the free parameter based on observation (of the Sun) and apply it to other situations where it seems to work pretty well. And I don’t think anyone would suggest that MLT was a good description of hydrodynamical simulations of convection. So I think work still needs to be done to connect the hydrodynamical picture of thermohaline mixing with what is currently being done in stellar evolution codes.

I feel I should point out the use of the word ‘diffusion’ in the question. The assumption is that we should treat thermohaline mixing as a diffusive process. It may be that thermohaline mixing is not diffusive in nature, and shouldn't be modelled as such. We treat it diffusively because it is easy to implement in our codes. We may find out that it is better treated by an advective scheme, as seems to be the case for our hydrodynamical simulations of convection in AGB stars.

Question from Pavel Denissenkov: How do you explain Li production in RGB stars?

Response: It is almost impossible to reconcile Li-rich RGB stars with the picture of mixing on the RGB being driven by thermohaline mixing. Thermohaline mixing tends to deplete lithium and it is very efficient at doing this in all stars. Lithium richness seems to be quite rare for giants, so it cannot be caused by a mechanism that operates in all giants. It seems more likely that some stochastic process is responsible for the Li-rich giants.

Question from Brian Fulton: At the start of the talk you discussed vibrations of gas volumes in a star, but in later part you show extensive turbulence in the medium. How do I sqaure these two views? Is it a timescale issue?

Response: For the solar-like oscillations I discussed, the former absolutely requires the latter. Something has to excite the various modes and that is the fluid motions in the convective envelope that are the driving force. The 'noise' of stellar convection translates into stochastic excitation of the various pulsational modes.