

STELLAR EVOLUTION - THE MULTIPLE ROLES OF STARS

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Version Feb 15, 2010

ABSTRACT

From modeling the remnants of the first generation of stars in the Universe to the analysis of the interior of the Sun using seismology, stars are playing a central role in many areas of astronomy. Within the embrace of astronomy, the coming decade offers the opportunity to make significant progress in areas such as multi-dimensional aspects of stellar evolution, for example in interacting binaries, or due to rotation, convection and magnetic fields. We will be able to test new models through qualitatively new asteroseismology data. All this will enable us to solve open questions, e.g., in nuclear astrophysics, in particular as they arise through observations of the most metal-poor stars that formed in the early Universe. We deliver comprehensive simulation data sets, for example for applications in stellar populations or galactic chemical evolution. Taking advantage of new observatories, some in space, as well as more powerful computers, stellar evolution is well positioned now to make significant new advances.

Subject headings:

1. GENERAL THEMES AND THE PAST DECADE

Stellar evolution has been at the centre stage of several important discoveries or scientific controversies over the past decade. Just as a reminder we mention the decades long quest for a solution of the solar neutrino problem, which was eventually settled in 2001 through critical measurements at the Canadian Sudbury Neutrino Observatory in favour of stellar evolution.⁵ Helioseismology has played an important role in reassuring astronomers, and we note in passing that this sensitive tool of probing the interior physics of stars is yet again involved in a controversy, this time concerning the solar abundance distribution (VandenBerg et al. 2007; Serenelli et al. 2009; Asplund et al. 2009).

Part of the controversy has been the role of 3D hydrodynamic model atmospheres, and these and the other ingredients of this latest solar problem combine some aspects of important achievements over the past decade with the themes for the coming decade: (i) Treating stars as three-dimensional objects; (ii) Probing the interiors of stars through asteroseismology and thereby constraining multi-dimensional physics in stars; (iii) Using stellar physics to infer the conditions for the origin of the elements in stars as well as the chemical evolution of galaxies, through abundance determinations from high-resolution spectroscopy.

1.1. *The evolving abundances of the stars and the Universe*

One area of enormous progress over the past decade has been the investigation of the origin of the elements in the first generations of stars, both observationally and theoretically. The discovery and detailed observation of the most metal poor stars, initially in the halo, and now in extra-galactic systems allows stellar evolution to play a fundamental role in several of the most active areas of astronomy: (i) The formation and

evolution of the first stars and their cosmological environment; (ii) Near-field cosmology - investigations of local structure through ancient stellar populations that reveal themselves through their chemical abundance and dynamical signatures⁶; (iii) Advancements in nuclear astrophysics from abundances in our own and other galaxies⁷.

Stellar abundances are a fundamental test of stellar evolution theory and their star formation environment since stars preserve a fossil record of the chemistry of their natal environments. The recent decade has seen tremendous advances in our observational knowledge about these first generations of stars. As the brief discussion of some main findings in Fig. 1 shows we are currently in the middle of working out the nucleosynthesis puzzle of galactic archeology.

This area of research is fast evolving, combining stellar abundance observations with new generations of simulations. With current 8-meter class telescopes we are able to extend this research to extragalactic systems (≤ 150 kpc Tolstoy et al. 2009). The power of this possibility has already been demonstrated by the DART collaboration (Fig. 2).

In nuclear astrophysics we are now on the verge of routinely calculating comprehensive data sets of nuclear yield production from all dominant nuclear production sites (Fig. 3)⁸. These are used to validate the underlying stellar evolution models, or to investigate still unknown nuclear production mechanisms. These yield sets need to be integrated in future abundance-based characterizations of stellar populations, as well as the next generation of dynamical galactic chemical evolution models. This research, however, is only possible with accurate nuclear data (Fig. 4).

Another frontier of stellar evolution tries to understand more extreme, short-lived and out-of-equilibrium modes of nucleosynthesis that are frequently encountered in simulations of the first generations of stars (e.g. Herwig et al. 2010), as well as flash-driven transient stellar events (as for example

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⁵ The experimental nuclear astrophysics program at TRIUMF continues important work on fully solving this problem, for example through the recent $^7\text{Be}(p,\gamma)^8\text{B}$ reaction rate measurement which largely determines the ^8B neutrino flux measured by SNO and Kamiokande.

⁶ Kim Venn & Alan McConnachie WP on stellar populations.

⁷ For complementary information ISM/IGM abundance analysis see Ellison WP.

⁸ For example, the NuGrid collaboration (<http://nugrid.phys.uvic.ca>) has developed a code infrastructure for internally consistent yield sets from both low-mass and massive stars, eventually including explosive yields.

X-ray bursts and novae). Canada's national nuclear physics laboratory TRIUMF has built up a leading role in radioactive beam facilities.⁹ For example, the pioneering measurements of $^{21}\text{Na}(p, \gamma)$ at TRIUMF are needed to explain the 1.275 MeV γ flux from novae (Fig. 5).

1.2. Stellar structure and evolution simulations

1.2.1. The one-dimensional spherically symmetric star

For several decades, stellar evolution has provided reliable predictions for many applications. The models generated by the University of Montreal group (e.g., Michaud et al. 2004), in particular, are still the only ones that take all of the most important diffusive processes (including radiative accelerations) into account. The current best estimate of the ages of the oldest stars in the Galaxy (≈ 13.5 Gyr, Fig. 6) is based on these models, which have also had notable success in explaining the detailed run of heavy-element abundances in the turnoff stars of globular clusters (provided that some additional turbulent mixing below convective envelopes is assumed Korn et al. 2007). One-dimensional models will continue to be indispensable as only they are capable of following many properties of stars extremely well over their entire lifetime.

Indeed, large grids of evolutionary tracks and isochrones have become an important tool to study stellar populations. They provide the basis for comprehensive nuclear yields calculations, initial models for supernova explosion calculations, initial conditions for multi-dimensional simulations of stars, observables for a wide range of stellar observations and the context for investigating exotic stars which are, for example, the outcome of interacting binary evolution. In an attempt to provide a modern and open code as a tool for research in all these areas Canadian researchers (Nelson, Dotter, Herwig) have joined the international MESA (Paxton et al. 2010) stellar evolution collaboration lead by researchers (Paxton, Bildsten) at KITP/UCSB, in order to provide the required, comprehensive data (Fig. 7).

The Canadian stellar evolution community offers expertise in binary stellar evolution as well (Ivanova, Sills). TWINS evolves two stars simultaneously (e.g. van der Sluys 2006) in order to study the products of massive stars mergers that could explain intermediate mass black holes in globular clusters (Glebbeek et al. 2009). For problems involving compact members the mass transfer is calculated implicitly (Ivanova & Taam 2004). An important success was the understanding of the period evolution in close binaries and fast rotating low-mass MS stars through a revision of the magnetic braking process (Ivanova & Taam 2003).

1.2.2. The multi-dimensional star

In the advanced phases of single stars or the interaction of binary stars or where non-spherically symmetric physics (in particular convection, rotation and magnetic fields) becomes important, 1D stellar evolution is inadequate. The last decade has seen what can only be the start of some real progress to address these challenges.

Two dimensional hydrodynamic simulations are used to investigate the evolution of rapidly rotating stars (Deupree & Karakas 2005; Toque et al. 2007). Such simulations allow us

to model the interior redistribution of composition and angular momentum both through short hydrodynamic time scales and longer thermal and evolutionary time scales. These models should be able to remove persistent uncertainties of current one dimensional models of rotating stars.

Convection in the He-burning shell of Asymptotic Giant Branch stars has been simulated in both 2D and 3D (Fig. 8 Herwig et al. 2006; Herwig et al. 2010) which already led to new insights on convective boundary mixing in advanced phases of stellar evolution. These simulations, including their nucleosynthesis analysis suggests that the fidelity of one-dimensional simulations of nuclear production of the first generations of stars should be reassessed.

Two and three dimensional hydrodynamic simulations of the core He flash (e.g. Deupree 1996; Dearborn et al. 2006; Mocák et al. 2009) all show noticeable downward convective overshooting into the neutrino cooled inner core. Because this is not included in traditional 1D models one may have to resort to a combination of implicit and anelastic methods to derive the starting models for the core flash simulations.

In the area of interacting binary research new simulations of collisions of compact stars with giants showed how ultra-compact X-ray binaries form (Ivanova 2006). Sills et al. (1997) used the outcome of hydrodynamic merger simulations to explain the evolutionary origin of blue stragglers. This emerging activity in 3D hydro-simulations that include the stellar interior represents an international trend (e.g. Meakin & Arnett 2007; Freytag & Höfner 2008; Brun & Palacios 2009).

1.3. Transient stellar evolution

Canada has secured a leading place in asteroseismology with the Canadian MOST (Microvariability and Oscillations of STars Walker et al. 2003; Matthews 2007) photometric satellite, which has been in continuous operation since June 2003. The collection of frequencies observed for individual stars provide significant constraints on the interior structure of pre-main-sequence (Zwintz et al. 2009), solar-type (Guenther et al. 2008), and giant stars (Zwintz et al. 2009), and improves our interpretation of specific classes of pulsating stars such as Wolf-Rayet (Moffat et al. 2008), roAp (Huber et al. 2008), delta Scuti (Pribulla et al. 2008) and SPBe (Cameron et al. 2008) stars.

However, success in matching observed frequencies depends on the fidelity of the underlying stellar evolution models, and in many cases not all frequencies can be accounted for. For rapidly rotating stars multi-dimensional models are therefore now developed and compared to asteroseismology observations (Lovekin et al. 2009).

The study of dense stellar systems (globular clusters, galactic centre) has evolved from a purely stellar dynamics problem to now include finite sizes of stars and the fact that stellar masses change with time. It was realized that in order to understand tellar exotica like blue stragglers, millisecond pulsars, and X-ray binaries, stellar and binary evolution as well as stellar dynamics calculations were required. Stellar evolution calculations of dynamically formed objects have been used to date the time of core collapse in a globular cluster (Ferraro et al. 2009).

The creation of the first thorough generation of binary population synthesis codes (e.g. Belczynski et al. 2002, 2008) as well as availability of the the supercomputer at CITA allowed to understand the formation and evolution of CVs and LMXBs in dense stellar environments – globular clusters

⁹ Significant fractions of this and new international facilities, notably FRIB at NSCL, Michigan at a cost of \$550 million and similar sized FAIR at GSI, Darmstadt, Germany will be available for nuclear astrophysics over the next decade.

(Ivanova et al. 2006, 2008). A continuing goal is to develop sub-grid calculations for the next generation of multi-physics, multi-scale stellar evolution/stellar dynamics simulations (e.g. MUSE, <http://muse.li>).

2. STELLAR EVOLUTION IN THE NEXT DECADE

2.1. *Simulating the stars*

Stellar evolution will continue its current path towards more realistic, multi-dimensional simulations that are bridging the time scale range in various ways. Already, we are using a range of techniques, from fully explicit grid codes, Lagrangian SPH methods, implicit 2D Lagrangian all the way to classic 1D fully implicit stellar evolution. As we move forward, meshing of different levels of simulation will play an important role. In the multi-D area, progress is now more rapid because simulation resolution has reached a critical limit and meaningful timescales can be followed.

Computationally, stellar HD simulations pose a special challenge due to the long time scales that have to be followed. Currently, modest production runs (e.g. Fig. 8) involve of the order 100,000 CPU hrs. However, new computing resources being installed now in the regional computing centers in Canada typically involve dozens of million CPU hrs, and south of the border peta-scale computing is coming now to NSF researchers, e.g. the Blue Waters machine at NCSA/Oak Ridge with some 6-digit number of computing cores. While such computing resources may not be available in Canada immediately one can clearly extrapolate that internationally the availability of computational resources will be a key driver for stellar evolution progress. If we can use such resources we will be able to solve the convection problem (including overshooting) in the next decade.

Asteroseismology will inevitably benefit from transient planet search missions (Kepler, CoRoT). The potential for validating simulations of the the interior structure of stars is enormous. Light curves of classical variable stars (e.g., RR Lyrae and Cepheid variables) depend on the interaction of convection and ionisation (particularly the hydrogen ionization zone) which is not accounted for even by a time dependent mixing length theory. Three dimensional large-eddy simulations to address this problem are currently under development in the US and Canada (Geroux & Deupree 2009).

2.2. *Observing the stars*

Observations of transient phenomena of stars, from explosions, mergers, or simply internal processes are expected to be second to none after the LSST survey, depending on the cadence applied in those observations. Spectro interferometric imaging of extended objects (VLTI, Keck Interferometer) reveals inhomogeneities in the outer atmospheres of variable stars and allow to differentiate 1D and 3D models (e.g., VX Sgr, Chiavassa et al. 2009).

In the near future, the APOGEE survey with SDSS-III will collect H-band spectra of stars in the Galactic centre to search for first stars. In the far future, IR and optical spectrographs on the TMT will make it possible to examine stars in more distant galaxies (M31, isolate gas-rich dwarfs).

Research in first generations of stars evolution would greatly advance if we could find more metal-poor stars. Ongoing and future dedicated surveys (like LAMOST) will multiply the yield of extremely metal-poor stars in our galaxy. But a very intriguing alternative requires an Hamberg/ESO like survey for metal poor stars in dwarf galaxies as described

in the Stellar Populations WP (Venn & McConnachie). Such a survey would have significantly stimulate stellar evolution and nuclear astrophysics research in Canada.

2.3. *Stellar evolution and other astronomy*

Given the importance of massive star and white dwarf SN it will be of particular importance to identify and understand the stellar evolution of their progenitors. The initial conditions for these events determine their outcomes, and are the result of the progenitor stellar evolution path. For SNIa the neutronization of the exploding material determines the peak brightness, and therefore the detailed nucleosynthetic progenitor evolution needs to be investigated.

More reliable AGB stellar evolution models are needed to correctly interpret colors and IR luminosities of high-redshift galaxies (Maraston et al. 2006; Tonini et al. 2009). Melbourne et al. (2010) establishes AGB stellar evolution properties as a tool to determine star formation histories even in distant galaxies, depending on the underlying model fidelity.

In order to fully exploit the promise of near-field cosmology, chemical tagging, and probing the early Universe through the first generations of stars we need a comprehensive framework for chemical evolution that takes full advantage of recent advances in structure formation as well as more available, and internally consistent yield sets.

Another interesting observational avenue for stellar evolution observations involves the use of integrated light spectroscopy of globular clusters (McWilliam & Bernstein 2009). Improvements in stellar evolution theory such that it is possible to predict accurate luminosity functions, and improvements in model atmospheres, will make composite spectrum syntheses of globular clusters more realistic. If detailed abundances can be determined from an integrated light spectrum of a globular cluster, then the TMT will make it possible to measure the chemical evolution of systems in the rich Virgo cluster of galaxies.

3. NEEDS FOR STELLAR EVOLUTION IN THE NEXT DECADE

Within some of the priority areas laid out in this white paper stellar evolution can only advance with continued access to high-resolution spectroscopy that can probe extra-galactic stellar evolution. In that regard the needs are the same as those formulated in the relevant recommendations of the Stellar Populations white paper by Venn & McConnachie.

Much of the activity covered in this WP relates to theory and simulation. A major emphasis in the next decade will be to quantitatively understand multi-dimensional properties of stellar evolution. With this focus, stellar evolution is among the computational disciplines of astronomy that would enormously benefit from a funding and infrastructure framework that has the goal to build-up and sustain a simulation science community in Canada. In addition, this direction of stellar evolution will require significant access to and availability of capability computing.

Demands for stellar evolution capabilities come from several areas, including first stars, stellar populations and galactic chemical evolution, nuclear astrophysics, progenitors for SN research as well as planetary research. Codes that incorporate our current understanding of the physics and algorithms are mostly available or are being developed/modified right now to fully take advantage of the latest generation of computing architectures. In particular the non-scientific nature of this last maintenance components of the more mature aspects of stellar evolution pose a challenge to the academic environment.

We like to thank Barry Davids, Chris Ruiz and Lothar Buchmann (TRIUMF) for their input on experimental nuclear astrophysics. Further, we would like to thank Tony Mof-

fat, Elizabeth Griffin, Gregg Wade, Gordon Walker, Suzanne Talon, Aaron Dotter, Marco Pignatari and Lorne Nelson for their interest, input and support.

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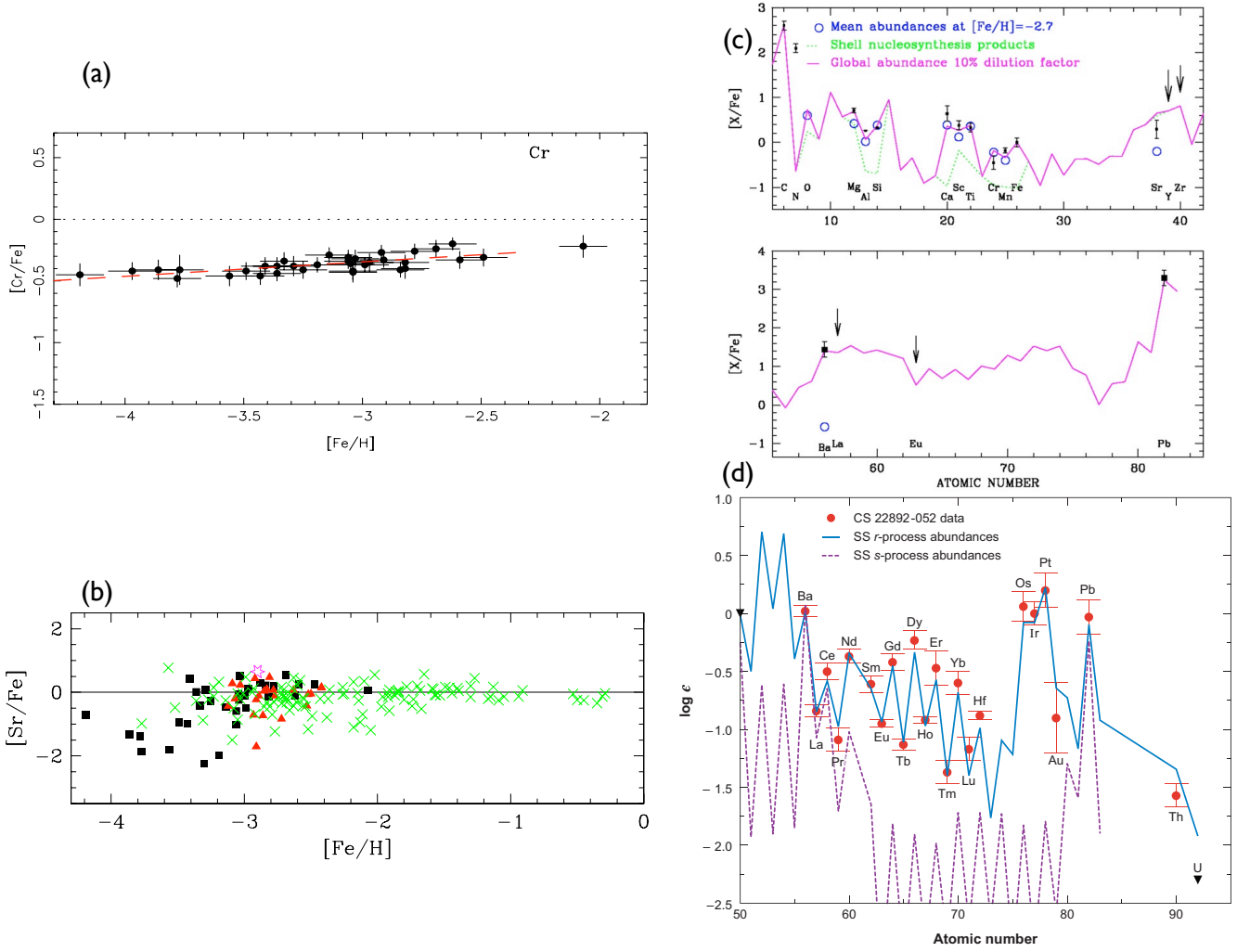


FIG. 1.— Examples of important observational results of first stars research over the past decade:

Panel (a): Elements associated with nuclear production in massive stars show surprisingly little scatter as a function of metallicity (Cayrel et al. 2004). By itself this could either imply efficient mixing of the ejecta of the first supernova or a very uniform nuclear production process.

Panel (b): Elements around Sr, Y, Zr however show a large scatter, which is increasing at lower metallicities (François et al. 2007). This implies that mixing of ejecta can not have been extremely efficient and that these elements have a different nucleosynthetic origin compared to Cr, for example. It is suggested that they originate from a different nucleosynthesis processes than the r process which has not yet clearly been identified (Lighter Element Primary Process, or LEPP, e.g., Pignatari et al. 2008, and reference therein), cf. top panel Sect. 4.

Panel (c): We now know that most of the stars with the extreme signatures in CNO elements and heavy elements have in fact been polluted from AGB binary companions that are now WD. These show extreme variations of overabundances of heavy elements, as for example the Lead (Pb) Star HE 0024-2523 (Lucatello et al. 2003).

Panel (d): Meanwhile, the main r-process component between Ba and Pb in several r-process rich stars of very low metal content resemble very well the solar r-process contribution (e.g., Sneden et al. 2008). However, from galactic chemical evolution studies the r-process is not typically associated with Fe production from massive stars (e.g., Travaglio et al. 2004, and reference therein).

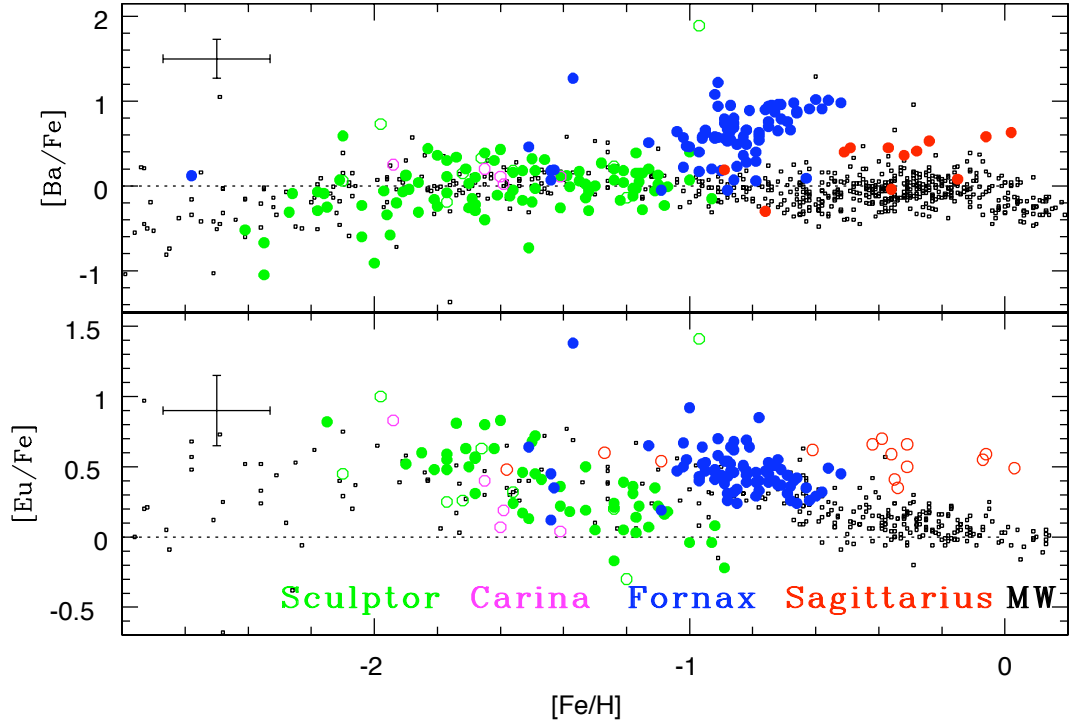


FIG. 2.— The DART collaboration used dwarf galaxies to study nuclear production processes and star formation histories (Venn et al. 2004; Tolstoy et al. 2009). Extra-galactic systems give us a new and unique tool to decouple degeneracies between nucleosynthesis, supernovae yields, HI infall, and star formation rates in interpreting chemical abundance trends. The late rise in Ba in the Fornax dwarf galaxy is due to the dominance of AGB contributions in a galaxy with recent star formation. Sculptor does not show this because it did not have recent star formation. The LMC shows this too (Pompéia et al. 2008).

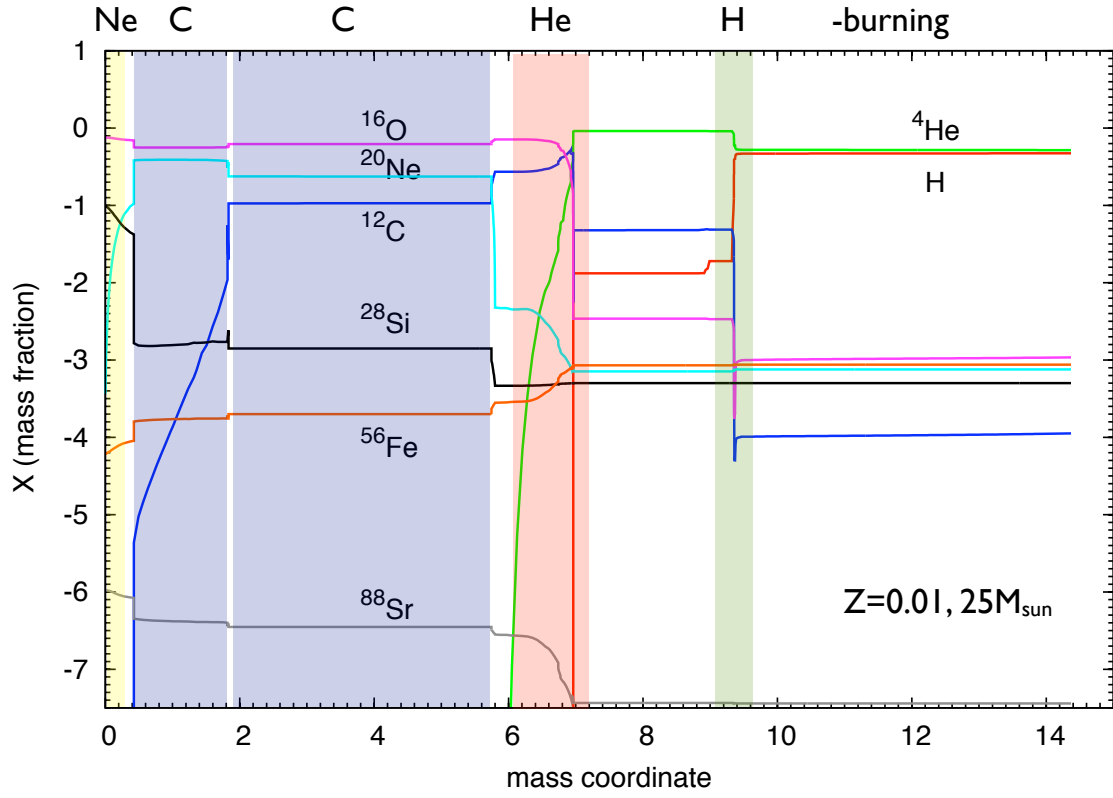


FIG. 3.— [Credit: NuGrid collaboration] Abundance profiles of $25 M_{\odot}$ stellar evolution model during Ne burning (burning zones are indicated at the top of the frame) according to full nucleosynthesis post-processing of massive star stellar evolution models (Fig. 7) using a new parallel post-processing nucleosynthesis code (PPN). The same code can be used for low-mass stars as well and will consider automatically all possible reactions. It uses a continuously updated compilation of nuclear data compilations.

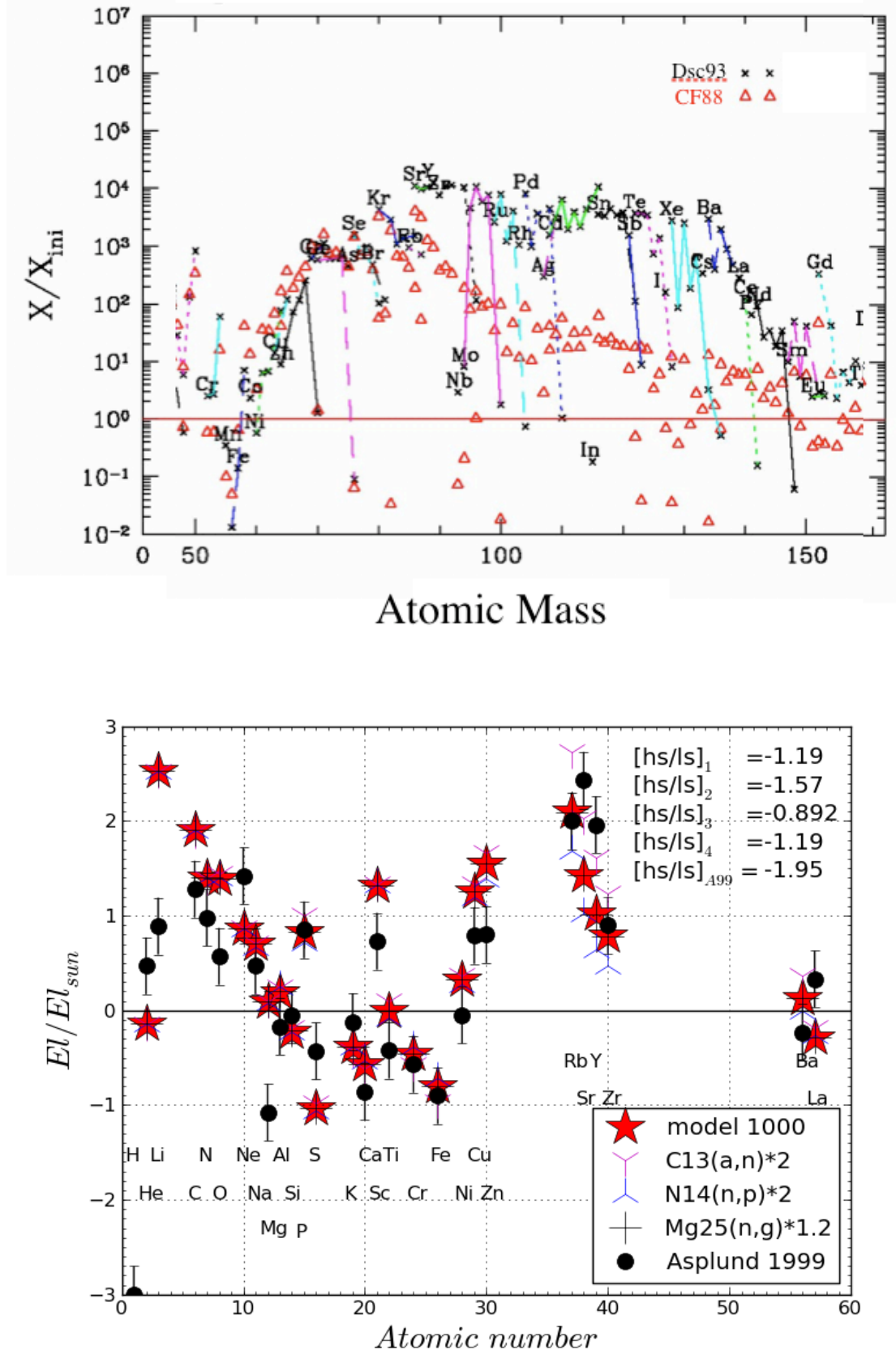


FIG. 4.— **Top:** The $^{17}\text{O}(\alpha, \gamma)^{21}\text{Ne}$ plays a critical role in the s-process in massive rotating stars of very low metallicity. However, this reaction has not been measured yet, and theoretical estimates by Descouvemont (1993) and Caughlan & Fowler (1988) differ by three orders of magnitude. In this example the heavy element production around and beyond the first neutron-magic peak at Y, Sr in a fast rotating stellar model of $[\text{Fe}/\text{H}] = -4$ is uncertain by a factor of 10 to > 100 , depending on atomic mass (Hirschi et al. 2008, NuGrid collaboration). This atomic mass range is exactly the one in which we currently can not account for the observed abundance signatures from metal poor stars (Sect. 1.1). Measurements of this rate are currently carried out at TRIUMF (Fig. 5).

Bottom: Convective-reactive burning of protons in ^{12}C -rich environments of He-burning, that occurs frequently in the most metal-poor stars (e.g. Iwamoto et al. 2004) is sensitive to nuclear reaction rate uncertainties. Herwig et al. (2010, NuGrid collaboration) have analysed the sensitivity of the complex multi-dimensional combustion nucleosynthesis in a similar flash event that occurs on young white dwarfs. They find that the key diagnostic ratio of heavy to light s-process elements ($[hs/ls]$) is uncertain by ~ 0.7 dex due to nuclear reaction rate uncertainties of some key reactions.

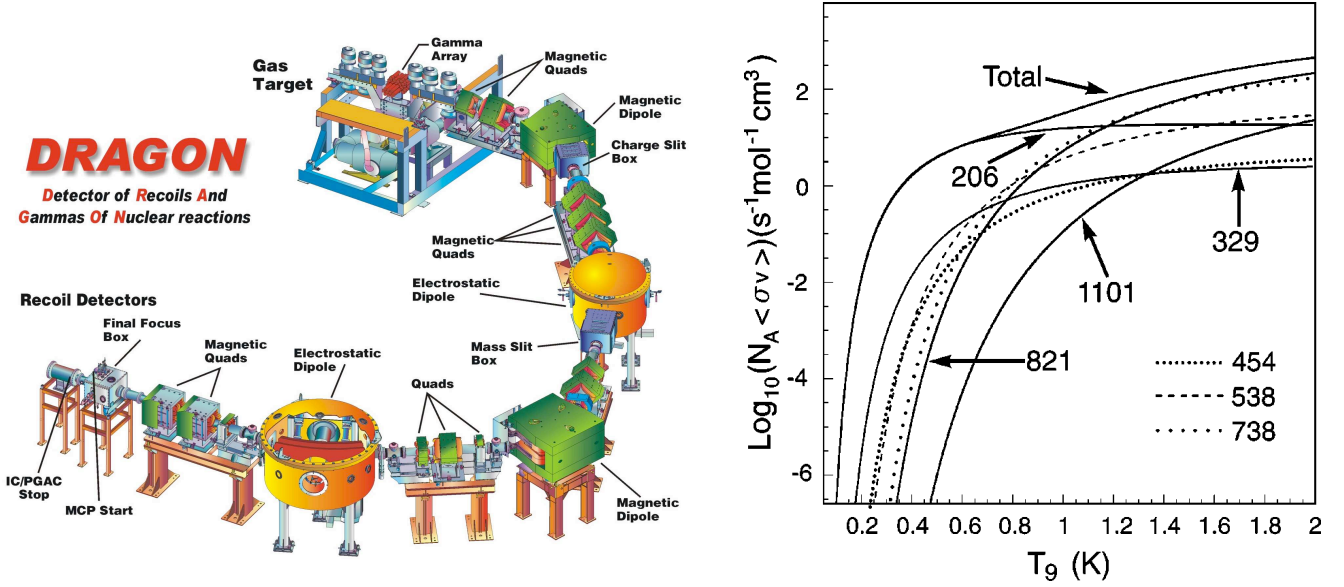


FIG. 5.— Experimental nuclear astrophysics facilities at TRIUMF provide critical nuclear data to address nuclear physics related simulation uncertainties as shown in Fig. 4. DRAGON at ISAC (left) measures radiative capture reactions, as for example the stellar reaction rate $N_A \langle \sigma v \rangle$ of the $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ reaction (D’Auria et al. 2004) in dependence of the stellar temperature in $10^9 \text{ K } T_9$. ‘Total’ indicates the total sum of all resonance contributions. Lines with numbers indicate individual resonance contribution in keV.

In addition there also has been emphasis on particle detection at ISAC with facilities like TUDA, and the newly developed TACTIC and NEURAL detectors. The latter two facilities are time projection chambers using either radioactive beams or neutrons to induce a reaction. TACTIC has recently been used to measure the $^{17}\text{O}(\alpha,\gamma)$ rate discussed in Fig. 4, and experimental data and astrophysical exploitation is currently under way.

As far as neutrons are concerned, a program has been started at ISAC to implant targets of longer lived radioactive nuclides either interesting as γ -emitters like ^{26}Al , meteoric inclusions like ^{41}Ca , or as branching points in the s -process path, e.g. in the nucleosynthesis of ^{36}S . The NEURAL detector is being developed to measure reactions of the (n,p) and the (n,α) kind on these radioactive, implanted targets at neutron-time-of-flight facilities, as for example at the Los Alamos Neutron Science Centre, LANL. Prioritization of experimental activity is guided by the theoretical nuclear astrophysics capability at the University of Victoria (Herwig).

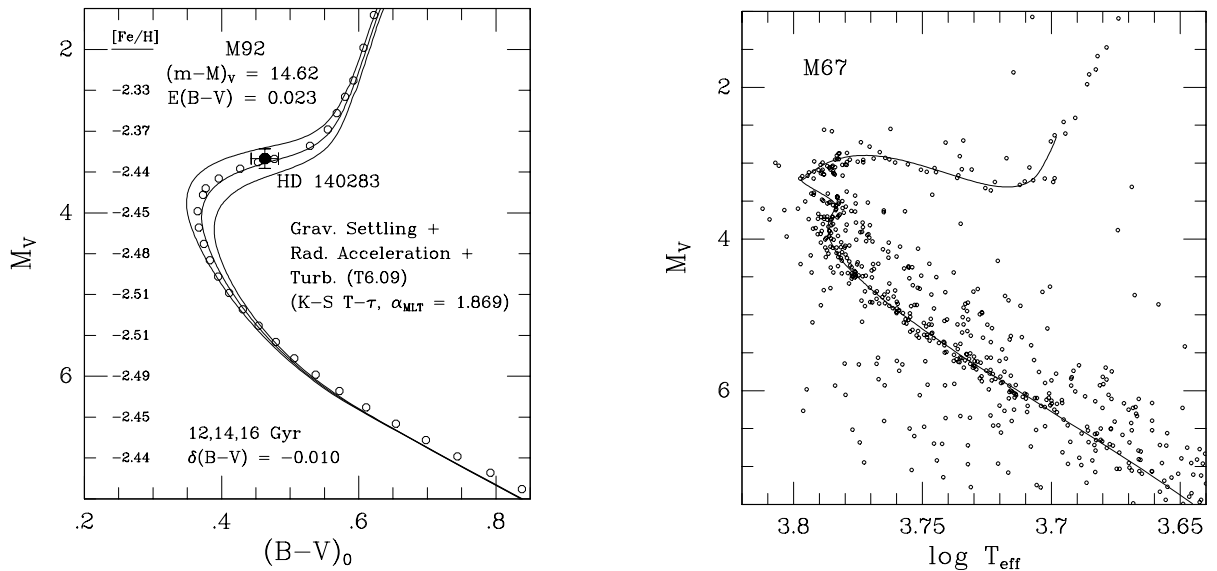


FIG. 6.— Comparison of diffusive isochrones computed by the University of Montreal group with observations of GC M92 and open cluster M67.

Left: The predicted variation of $[\text{Fe}/\text{H}]$ as a function of M_V along the 14 Gyr isochrone is indicated along the ordinate (VandenBerg et al. 2002). When atomic diffusion is included surface abundances provide an additional constraint on such hydrodynamical processes as turbulence and meridional circulations within stars.

Right: [Credit: D. A. VandenBerg] The temperatures of the cluster stars were derived from the latest empirical calibrations of V-K vs. T_{eff} (Casagrande et al. 2010). The distance is derived from the main sequence fit while the cluster $[\text{Fe}/\text{H}]$ is known from spectroscopy. The close match between simulation and observations of the turn-off and subgiant stars demonstrate the predictive power of today’s stellar evolution models for these applications.

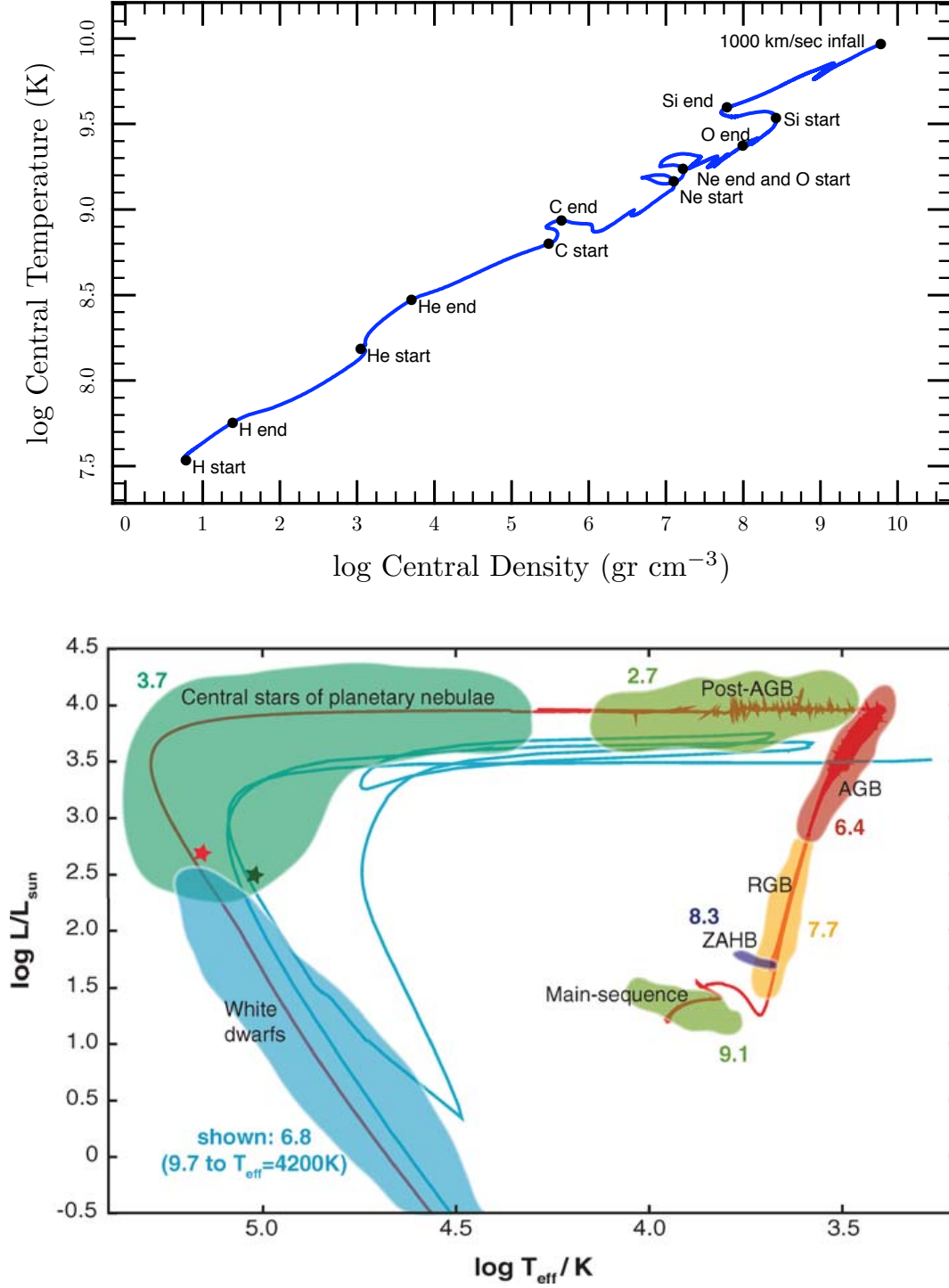


FIG. 7.— **Top:** MESA stellar evolution hands-off of central conditions in a $15 M_{\odot}$ star from the main-sequence to core-collapse [credit: Bill Paxton, KITP]. While such simulations are not qualitatively new, it is new that the shown evolutions leading up to the SN explosion (and the white dwarf stage respectively,) only take several hours on a dual-core machine with the same, modern and open source MESA code (Paxton et al. 2010). If supported properly in the future this code will satisfy a significant fraction of the future general purpose stellar evolution needs in a computationally very efficient way that can eventually be integrated into more comprehensive models.

Bottom: Complete low-mass stellar evolution (Herwig 2005).

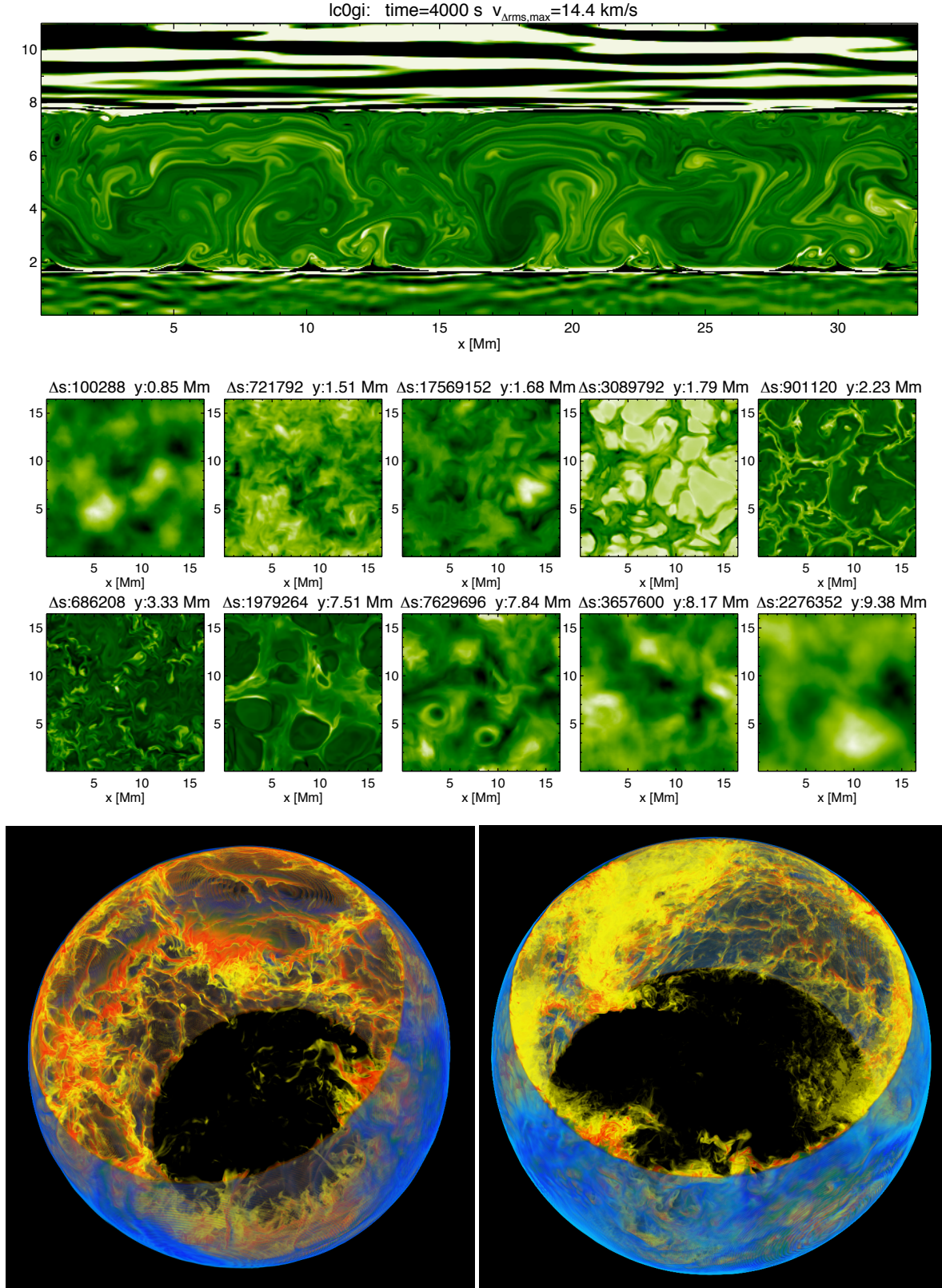




FIG. 9.— Following the unexpected seismic results from MOST of Procyon, new 3D hydrodynamical models of Procyon's outer convective region were constructed revealing significantly different thermodynamic structure in the superadiabatic layer to that of the Sun, which helped reconcile the space and ground-based seismic observations. The figure shows a snapshot of Procyon's convective envelope as seen from the side, with hot (lighter coloured) material rising from the bottom and long narrow plumes falling from above (Robinson et al. 2005).