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# Stellar Structure, Evolution and Nucleosynthesis: Key Uncertainties and their Impact

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After a brief introduction, we focus on a few key physical ingredients for the evolution of stars and the related nucleosynthesis, namely mass loss, convection and rotation. We first review the current status of their uncertainties and then discuss their impact. Concerning convection, we list key existing and future 3D hydrodynamics simulations needed to constrain prescriptions used in the modelling of convective boundaries in 1D codes. We then discuss the impact of rotation on the s process in both massive and low-mass stars. Massive star models including rotation-induced mixing reproduce much better several observational constraints (e.g. primary nitrogen production and boosted weak s process). AGB models including rotation, on the other hand, fail to produce s process although codes using different prescriptions yield contradictory results. The inclusion of the interaction of rotation with magnetic fields has a positive effect on the predicted spin of white dwarfs. We investigated the impact of this interaction on the $^{13}$C-pocket and find that magnetic fields may also help rotating stars produce more (rather than less) s-process. Current uncertainties in the treatment of convection, rotation and magnetic fields limit the predictive power of stellar evolution models and different implementations in codes lead to different results. Combining 3D hydrodynamics simulations and theoretical work with observational constraints will be needed to improve the situation. In this context, nucleosynthetic signatures of these processes will play a key role as they have up to now.

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## 1. Introduction

Stars are the furnaces, in which most chemical elements are produced. Starting with hydrogen, helium and traces of light metals produced during the big bang, nuclear fusion reactions in stars produce elements up to the iron peak. Furthermore, slow neutron capture processes enable the production of about half of the elements heavier than iron. The other main site of nucleosynthesis is supernova explosions, that marks the death of stars. The production of chemical elements is therefore closely linked to the evolution of stars and progress in both nuclear physics and stellar astrophysics is necessary to tackle the challenging question of the origin of the elements.

The key properties of a star are its mass, metallicity, rotation rate and multiplicity. The mass is the most important of these and will determine the evolution and fate of a star. Massive stars ($M \gtrsim 9 M_\odot$, see [1, 2] and references therein for more details on the transition between massive and intermediate mass stars) go through all the hydrostatic burning stages from hydrogen to silicon burning and form an "iron"-core (composed of iron-group elements). Since no more nuclear binding energy can be extracted via fusion reactions, the core will collapse and later on often explode. As the initial mass of a star decreases, its centre become degenerate earlier during its evolution. In a very degenerate core, contraction leads to cooling rather than heating. For this reason, low- and intermediate-mass stars ($M \lesssim 9 M_\odot$) do not reach high enough temperature to go through all the burning stages and they leave behind a white dwarf (WD) [3]. The composition of the WD depend on their late evolution. Super-AGB stars ($8 M_\odot \lesssim M \lesssim 9 M_\odot$) undergo off-centre carbon burning and produce WDs rich in C-burning products: Ne, Na, Mg, Al [4]. Less massive stars stop after helium burning (which starts off-centre for low-mass stars, $M \lesssim 1.8 M_\odot$) and produce WDs rich in carbon and oxygen. The other key properties listed above will also affect the evolution and fate of stars and the mass limits given above are not sharp but also functions of the metallicity (see e. g. [5]), rotation rate (see [6, 7, 8, 9, 10] and multiplicity [11, 12]. The mass limits and stellar evolution are also affected by uncertainties linked to the modelling of the key physical ingredients, in particular convection [13, 14] and mass loss.

The topic of stellar evolution is too large to cover in these proceedings. The reader is referred to the citations given in the last paragraph for a non-exhaustive list of the studies published since the last NIC. In these proceedings, we will focus on a few key physical ingredients, namely mass loss, rotation and convection. We will discuss their impact on the evolution and nucleosynthesis as well as their uncertainties.

## 2. Key physical ingredients and their uncertainties

Stellar evolution modelling requires many physical ingredients: mass and energy conservation and transport laws, nuclear reactions, convection, rotation, magnetic fields, mass loss, binary interactions, equation of state, opacities and neutrino energy losses. Many ingredients are not modelled self-consistently in stellar evolution calculations. Instead, prescriptions, based upon other simulations and theory, are implemented in stellar evolution codes. Thus such prescriptions have important uncertainties and free parameters that need to be calibrated and constrained. This is the case for mass loss, rotation and convection, which are reviewed in these proceedings.

### 2.1 Mass loss

Mass loss driving mechanisms depend mainly on the luminosity and the surface temperature of stars ($T_{\rm eff}$). In hot stars ($T_{\rm eff} \gtrsim 10,000$), winds are generally driven by the interaction of light with atomic lines (radiatively line-driven winds). Theoretical prescriptions for hot O-type [15] and WR-stars [16] are commonly used and they compare rather well with observations [17, 18], especially for O-type stars. Uncertainties are thus relatively small compared to other phases and relate mainly to the clumpiness of the winds. Note that this small uncertainty can still have a significant impact given the timescale of the O-type and WR phases. Line-driven winds depend on the surface iron content in the star, which does not vary during the evolution of the star, and thus have a clear dependence on the initial metallicity ($Z$). For example, LMC ($Z = 0.006$) and SMC ($Z = 0.002$) stars are expected to have mass loss rates, which are $1.5-2$ and $2.5-5$ times smaller than solar-metallicity stars ($Z_\odot = 0.014$), respectively. At low $Z$, the surface abundance of carbon, nitrogen and oxygen may play an important role [19]. In cool(er) stars ($T_{\rm eff} \lesssim 10,000$), the driving mechanism is not fully understood but pulsation and dust are thought to play a central role. Continuum-driven winds could also play a role in very luminous blue variable stars. Mass loss prescriptions for cool stars are mostly based on observations. The most commonly used prescriptions are [20] for red-supergiant stars, [21] with $\eta \sim 0.5$ for red giant and [22] with $\eta \sim 0.05-0.1$ for the superwind phase in asymptotic giant branch stars. Uncertainties for cool-star winds are larger and not precisely known since the driving mechanism is not fully understood. The metallicity-dependence of cool-star winds is also not clear [23].

### 2.2 Convection

The modelling of convection in 1D stellar evolution models involved three main aspects: 1) energy/heat transport in convective zones, 2) determining the location of convective zone boundaries and 3) Additional mixing across the formal 1D convective boundary, which we will call convective boundary mixing (CBM).

1) The energy transport in convective zones is usually based on the mixing-length theory (MLT) developed by Böhm-Vitense around 1958 [24]. This theory was developed without the knowledge of the work of Kolmogorov on turbulence cascade (see [25] and references therein for more details). The MLT assumes that there is a single representative mixing length, $\ell_{\rm mlt}$, which is thought to be not too far from a pressure scale height, $H_P$: $\ell_{\rm mlt} = \alpha_{\rm mlt} H_P$, $\alpha_{\rm mlt}$ being a free parameter calibrated by observations. It is well known, however, that a turbulence cascade involves many length scales. One of the major attempts at superseeding MLT in stellar evolution code is the full-spectrum theory (FST) by [26]. In the stellar interior, the temperature gradient is very close to the adiabatic gradient so the impact of new theories is limited but convective envelopes will depend significantly on the theory used and the mixing length (see e. g. [27]). A recent approach to remove the use of the mixing length parameter for the outer convective zone of the Sun is the work of [28].

2) MLT does not determine the location of the convective boundary. In order to locate it, the Schwarzschild or Ledoux criteria are used, the latter including the effect (generally stabilising) of the mean molecular weight ($\mu$) gradients. Hydrodynamics simulations (e.g. [29, 30]) show that there is mixing beyond the formal Ledoux convective boundary, which reduces the $\mu-$gradient

effects. Since this is the case, several groups use the Schwarzschild criterion for convection (e.g. [31, 8]).

3) Theory suggests that there is even mixing beyond the Schwarzschild boundary since the acceleration of a fluid element is zero at the boundary but not its velocity. Furthermore stellar evolution models usually include some kind of convective boundary mixing (CBM) in order to reproduce the width of the observed main sequence. For example, overshooting is often used to extend the size of convective cores by a fraction $\alpha_{\rm OV}$ of the pressure scale height (e.g. $\alpha_{\rm OV} = 0.1\,H_P$ in the Geneva code, [6]). Since overshooting occurs on a dynamical time scale, it is often considered as instantaneous in stellar evolution calculations. Simulations from [29] show that penetrative mixing is better represented as a time-dependent process with a certain entrainment rate. Overshooting is a kind of penetrative mixing, in which the boundary is displaced but it remains a sharp boundary. Other processes may soften the boundary. Indeed, as a fluid element approaches the convective boundary, it turns around and for a while moves parallel to the boundary, thus creating a shear layer. If the velocity gradient across the boundary is strong enough, Kelvin-Helmholtz instability may soften the boundary and mix material across it. This second type of CBM is implemented in AGB simulations in the form of an exponentially-decaying diffusion coefficient (see [3, 30]). An extended and mild mixing is necessary to produce a large enough $^{13}$C-pocket to reproduce observations [32]. Other AGB groups treat CBM in other ways (see e. g. [33]).

#### 2.2.1 Priority list for 3D hydrodynamics simulations

The real situation is probably a combination of the two types of CBM (entrainment and shear mixing). Targeted 3D hydrodynamics simulations are needed to constrain convective transport, boundaries and mixing across the boundary in the various phases of stellar evolution. A non-exhaustive priority list is the following:

- Core hydrogen burning: This is the longest lasting phase and many observational constraints are available (main-sequence width, asteroseismic determination of convective core extent). Unfortunately, this is a very hard phase to model since radiative effects are important and cannot be ignored. Also the convective turn-over time scale and stellar evolution time scale are longest for this phase. This phase has been investigated by e. g. [29, 34]. Note that the core helium burning phase represents similar challenges.

- AGB thermal pulses and hydrogen-ingestion events: The AGB phase is important for the main s process and the 1D hydrostatic assumption made in stellar evolution models becomes invalid, especially in the case of hydrogen-ingestion in late thermal pulses. This phase is already being investigated by several groups [35, 36, 37]. Although radiation is still the main mode of energy transport in this phase (as opposed to neutrinos in the advanced phases in massive stars), the extremely high luminosities at the bottom of the convective zones reduces the importance of radiative effects so that it is not crucial to include them in simulations. The main limitation of TP-AGB simulations is the extent to which results in this phase can be extrapolated to other phases of stellar evolution.

- Silicon burning: This phase is the last phase before the supernova explosion and 3D asymmetries in the progenitor structure might help the explosions of massive stars (see e.g. [38, 39]).

Furthermore, possible shell mergers occurring after core Si-burning [40, 14] may strongly affect the compactness of the star at collapse as well as the weak s-process yields. In this phase, the energy is evacuated by neutrinos so radiative effects can be ignored. On the negative side, many nuclear reactions take place during this phase and a large nuclear reaction network is needed to follow properly the energy generation. Furthermore the structure at the start of Si-burning may be affected by the history of convective shells (linked to C, Ne, and O-burning phases), which could affect the initial conditions of the 3D models.

- Oxygen shell burning: has the same advantages as the Si-burning phase. In addition a smaller network may be used to track the energy production. On the negative side, the structure of the input models for 3D hydrodynamics simulations may also be affected by the previous convective shells history. This phase is being studied by [29, 13].

- Carbon shell burning: This is the first phase for which neutrinos dominate the energy transport and thus radiative effects are small and may be ignored. The carbon shell proceeds in a region that was part of the helium-burning core. Its initial structure is thus not affected by previous convective shells like the more advanced phases. Finally, it is the zone in which the weak s process takes place. We have started investigating this phase and initial results are presented in [41].

- Convective envelope in solar-type and cool stars: Although this is less important for nucleosynthesis, these stars and their modelling may be strongly affected by 3D effects [42, 43, 13] and their study in 3D has started a long time ago. 3D studies have in particular lead to the downward revision of the solar abundance [44].

The list above focuses on single stars. Binary interactions in general and the common envelope phase in particular (see [45, 46, 47] and references therein) are also important processes to tackle in multi-D simulations.

### 2.3 Rotation and magnetic fields

The physics of rotation included in stellar evolution codes has been developed extensively over the last twenty years. A recent review of this development can be found in [7]. The effects induced by rotation can be divided into three categories.

1) **Hydrostatic effects**: The centrifugal force changes the hydrostatic equilibrium of the star. The star becomes oblate and the stellar structure equations have to be modified but by assuming shellular rotation, the problem can still be treated with one-dimensional equations.

2) **Mass loss enhancement and anisotropy**: Rotation, via the centrifugal force, reduces the surface effective gravity at the equator compared to the pole. As a result, the radiative flux of the star is larger at the pole than at the equator. In massive hot stars, since the opacity is dominated by the temperature–independent electron scattering, rotation enhances mass loss at the pole. If the opacity increases when the temperature decreases (in cooler stars), mass loss can be enhanced at the equator when for example the bi-stability [15] is reached. Enhancement factors of the winds due to rotation are generally close to one but they may become very large when $\Gamma \gtrsim 0.7$ or $\Omega/\Omega_{\rm crit} > 0.9$ (see [48, 49] for more details). If critical rotation, where the centrifugal force balances gravity at

the equator, is reached, mechanical mass loss may occur and produce a decretion disk (see [50] for more details). In most stellar evolution codes, the mass loss is artificially enhanced when $\Omega/\Omega_{\rm crit} \gtrsim 0.95$ to ensure that the ratio does not become larger than unity but multi-dimensional simulations are required to provide new prescriptions to use in stellar evolution codes.

3) **Rotation-driven instabilities**: The main rotation driven instabilities are horizontal turbulence, meridional circulation and dynamical and secular shear (see [51] for a comprehensive description of rotation-induced instabilities). Horizontal turbulence corresponds to turbulence along the isobars. If this turbulence is strong, rotation is constant on isobars and the situation is usually referred to as “shellular rotation” [52]. The horizontal turbulence is expected to be stronger than the vertical turbulence because there is no restoring buoyancy force along isobars. Meridional circulation, also referred to as Eddington–Sweet circulation, arises from the local breakdown of radiative equilibrium in rotating stars. This is due to the fact that surfaces of constant temperature do not coincide with surfaces of constant pressure. Indeed, since rotation elongates isobars at the equator, the temperature on the same isobar is lower at the equator than at the pole. This induces large scale circulation of matter, in which matter usually rises at the pole and descends at the equator. The long term sustainability of meridional currents is due to torques linked to the evolution of the star and stellar winds (see [53] for a more in depth discussion of meridional circulation driving). Circulation corresponds to an advective process, which is different from diffusion because the latter can only erode gradients. Advection can either build or erode angular velocity gradients (see [54] for more details).

Dynamical shear occurs when the excess energy contained in differentially rotating layers is larger then the work that needs to be done to overcome the buoyancy force. If the differential rotation is not strong enough to induce dynamical shear, it can still induce the secular shear instability when thermal turbulence reduces the effect of the buoyancy force. The secular shear instability occurs therefore on the thermal time scale, which is much longer than the dynamical one. Note that the way the inhibiting effect of the molecular weight ($\mu$) gradients on secular shear is taken into account impacts strongly the efficiency of the shear. In some work, the inhibiting effect of $\mu$–gradients is so strong that secular shear is suppressed below a certain threshold value of differential rotation [55]. In another works [56], thermal instabilities and horizontal turbulence reduce the inhibiting effect of the $\mu$–gradients. As a result, shear is not suppressed below a threshold value of differential rotation but only decreased when $\mu$–gradients are present.

The various prescriptions for rotation-induced instabilities and the implementation of the meridional circulation as an advective or a diffusive process may lead to different results. [57, 8, 58] showed that the results depend significantly on the prescriptions used. Thus more work is needed to better constrain these prescriptions.

#### 2.3.1 Interaction between rotation and magnetic fields

A key question for the evolution of massive stars is whether a dynamo is at work in internal radiative zones. This could have far reaching consequences concerning the mixing of the elements and the transport of angular momentum. In particular, the interaction between rotation and magnetic fields in the stellar interior strongly affects the angular momentum retained in the core and thus the initial rotation rate of pulsars and which massive stars could die as long & soft gamma-ray bursts (GRBs), see the discussion in Sect. 6 in [59] (and references therein).

The interplay between rotation and magnetic field has been studied in stellar evolution calculations using the Tayler–Spruit (TS) dynamo [60, 61]. Some numerical simulations confirm the existence of a magnetic instability, however the existence of the dynamo is still debated [62, 63]. Without magnetic field, the star has a significant differential rotation already on the main sequence, while $\Omega$ is almost constant when a magnetic field created by the dynamo is present. It is not perfectly constant, otherwise there would be no dynamo. In fact, the rotation rapidly adjusts itself to the minimum differential rotation necessary to sustain the dynamo. One could then assume that the mixing of chemical elements is suppressed by magnetic fields. This is, however, not the case since the interplay between magnetic fields and the meridional circulation may lead to more mixing in models including magnetic fields compared to models not including magnetic fields [61]. Fast rotating models of GRB progenitors calculated by [64] also experience a strong chemical internal mixing leading to the stars undergoing quasi-chemical homogeneous evolution. The study of the interaction between rotation and magnetic fields is still under development. For example, [65] consider a different rotation-magnetic field interaction theory, the $\alpha - \Omega$ dynamo, and study its impact on stellar evolution. Another effect could come from the coupling of the magnetic field attached to the core with layers surrounding the core as investigated by [66]. An external magnetic field may also have an impact on the evolution of the surface velocities and abundances through the process of wind magnetic braking [67, 68]. The next ten years will certainly provide new insights on this important topic.

## 3. Nucleosynthesis in rotating stars

During their evolution, stars contribute to the production of elements heavier than iron via slow neutron captures intertwined with beta-decays, the so-called s process. The main component of the s process takes place during the TP-AGB phase in low and intermediate mass stars and the weak component in core helium and shell carbon burning in massive stars (see [69] for more details). Key parameters of the s process are seeds (usually iron), neutron source and neutron poisons, which vary according to the burning stage and metallicity. In these proceedings, we focus on the effects of rotation (and magnetic fields) on both the weak and main s process.

### 3.1 Rotation-boosted weak s process in massive stars

The weak s process in massive stars mainly produces elements with atomic mass, $60 \lesssim A \lesssim 90$. The main neutron source in this case is the $^{22}$Ne$(\alpha,n)$ reaction. Many studies have determined the weak s-process yields in non-rotating stars (see references in [69]). At solar metallicity ($Z_{\odot}$), the effects of rotation on the weak s process are moderate since large quantities of $^{22}$Ne are produced by two $\alpha$-captures on the CNO elements initially present in the ISM when the star is formed. At low $Z$, less and less CNO is initially present in the star and in non-rotating models, the production falls steeply. In rotating models, mixing takes place between the helium-burning core and the hydrogen-burning shell, leading to a significant production of primary nitrogen and $^{22}$Ne [70]. In [71] and [72], we showed that this leads to an important production of elements not only up to the strontium peak but even up to the barium peak. GCE models including the rotation-boosted weak s-process yields are able to reproduce the observed [Sr/Ba] scatter in EMP stars. This represents the fifth signature of fast rotation in low-$Z$ massive stars after rise of N/O and C/O, low $^{12}C/^{13}$C,

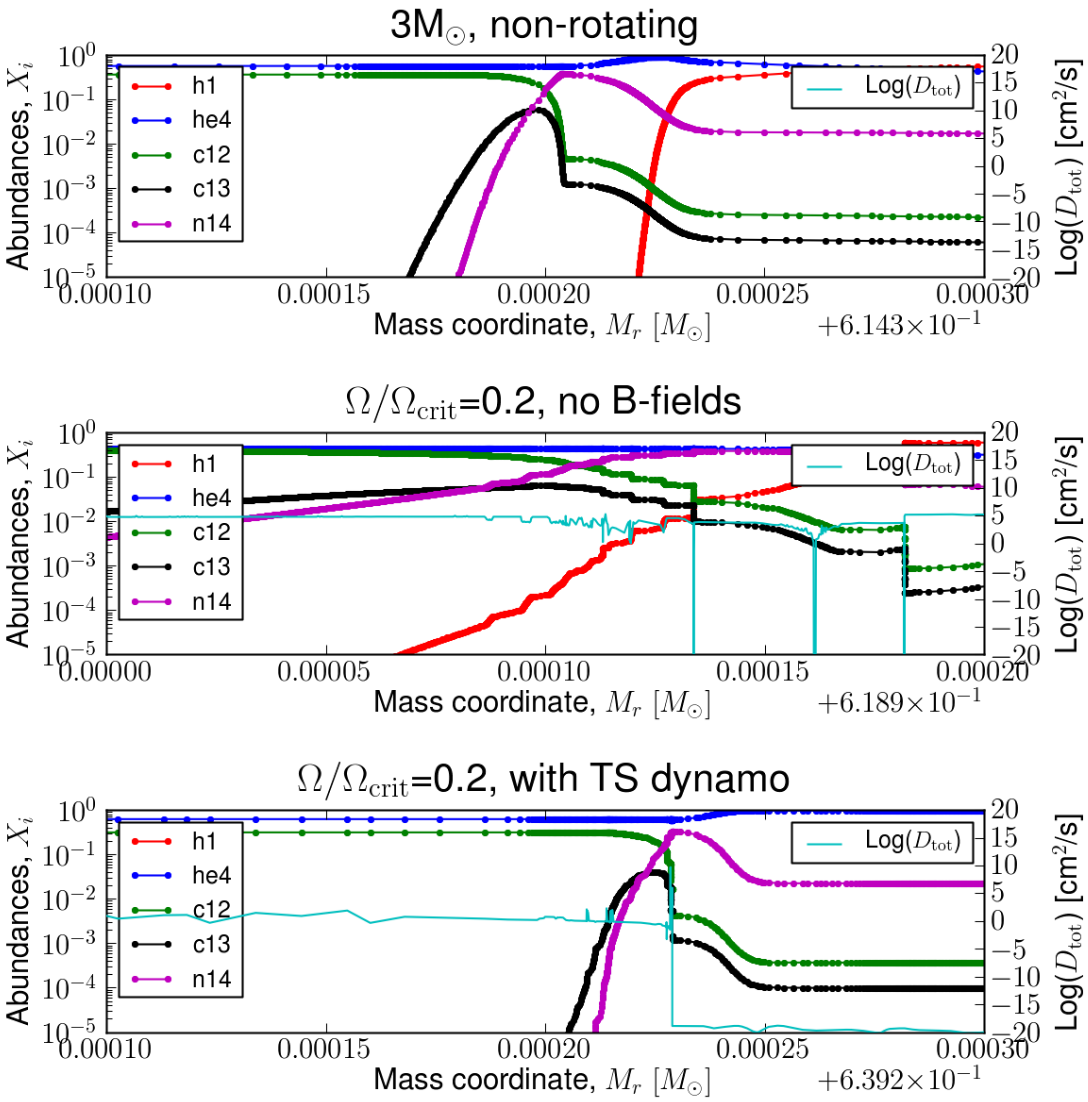


**Figure 1:** Abundance profiles across the $^{13}$C-pocket in 3 $M_\odot$, solar-metallicity, models without rotation (*top-panel*), with rotation ($\Omega_{ini}/\Omega_{crit} = 0.2$, *middle-panel*) and with rotation and the TS dynamo (*bottom-panel*). Note that the same mass range extent is plotted in the three panels. The total diffusion coefficient (cyan colour) for mixing due to rotation and magnetic-fields is also plotted (right-hand side scale).

and a primary-like evolution of Be and B [73]. Thus models including rotation better reproduce observations compared to non-rotating models. Key nuclear uncertainties in this context are $\alpha$-capture rates on $^{17}$O and $^{22}$Ne (see [74]). The initial results of a large scale uncertainty study is presented in Nishimura's contribution in this volume, id 127).

### 3.2 Does rotation kill the s process in AGB stars?

In AGB stars, the bulk of the s process is produced in the $^{13}$C-pocket, which forms just after the dredge-up in the TP-AGB phase [75, 3, 32]. A typical pocket in a non-rotating $3\,M_\odot$ model at $Z_\odot$ calculated with the MESA code (revision 6208, [9]) is shown in the top panel of Fig. 1. The $^{13}$C in the pocket later on burns via $(\alpha,n)$ and enables the production of s process as long as the $^{14}$N abundance in the pocket is low enough [76]. Contrary to the situation in massive stars, the inclusion of rotation in low mass stars is counter-productive. Indeed, efficient rotation-induced mixing in this radiative zone first broadens the $^{13}$C-pocket. This is shown in the middle panel of Fig. 1. This could lead to more s-process production but further mixing (with a diffusion coefficient of the order of $10^5$ cm$^2$/s) leads to the poisoning of the pocket with $^{14}$N. Our model thus confirms the results of [77]. Other groups, using a different implementation of rotation-induced mixing, find that s process production is increased for not-so fast rotating stars [33], which contradicts the above results.

Another problem of rotating models without magnetic effects is that they rotate too fast compared to compact remnant and asteroseismic observations (see [78, 79, 80, 81, 82, 83] and references therein). Several groups have thus introduced the Taylor-Spruit (TS) dynamo [60] in their models and have obtained better agreement with the spin-rate of compact remnants (see e.g. [78, 84, 85]). Their results indicate that including the TS dynamo is a step in the right direction but a stronger coupling is needed to reproduce observational constraints. In the bottom panel of Fig. 1, we show the $^{13}$C-pocket in a model including the TS dynamo. We can see that the extent of the pocket is much more similar to the non-rotating model than to the rotating model without magnetic fields. In this case, the total diffusion coefficient for mixing is much smaller than in the model without the TS dynamo, of the order of 1 cm$^2$/s, which does not lead to significant poisoning of the pocket. Although further investigations are needed, our initial results indicate that also for s-process production, including magnetic fields is a step in the right direction. The different results obtained by different groups and between models with and without magnetic fields clearly show that more work needs to be done to better constrain the rotation-induced mixing and the interaction between rotation and magnetic fields.

## 4. Conclusions and outlook

As mentioned at the start of these proceedings, the production of chemical elements is closely linked to the evolution of stars and progress in both nuclear physics and stellar astrophysics is necessary to tackle the challenging question of the origin of the elements. Progress in one field can be made with the help of the other. One may constrain nuclear physics uncertainties and determine their impact by using stellar evolution models as virtual nuclear physics laboratories (see e. g. [86, 40]). At the same time, nucleosynthesis signatures can help constrain stellar evolution models (see e. g. [72]). Future targeted 3D hydrodynamics simulations as well as stellar abundances and asteroseismic observations will also be key to make progress in the field. Beyond the physics of

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stellar models, the accumulation of nucleosynthetic products in the ISM contains information of the integrated past star formation history and thus part of the evolution of the galaxies.

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