Hidden dynamo spins down radiative stars

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The life and death of a star are controlled by its internal rotation dynamics through subtle transport and mixing mechanisms, which so far remain poorly understood. While magnetic fields must play a crucial role in transporting angular momentum and chemical species, the very origin of magnetism in radiative stellar layers and its influence on spinning dynamics are yet to be unraveled. Using global numerical modeling, we report the existence of a dynamo sharing many characteristics with the (never observed) Tayler-Spruit model, which can generate strong magnetic fields and significantly enhance transport in radiative zones. The resulting, deep toroidal fields are screened by the outer medium, allowing for the existence of intense magnetism in radiative stars where no magnetic fields could be directly observed so far.

Introduction The transport of angular momentum plays a crucial yet mysterious role in the evolution of stellar systems. As ageing stars evolve away from the main sequence, their rotation profile develops strong gradients: the core, running out of hydrogen fuel for nuclear fusion, contracts and spins faster, whereas their external layers expand and slow down (I). Similarly, young
stars are also expected to experience core spin-up due to the combined effects of accretion and the conservation of angular momentum during their formation stage. Owing to the recent rise of asteroseismology techniques (2–4), a growing amount of observations have however shown that rotation profiles of both main sequence and post-main sequence stars are significantly flatter than they ought to be based on stellar evolution models, especially across radiative zones, and that their cores rotate significantly slower (5–7). This suggests the existence of a powerful mechanism capable of extracting angular momentum from the stellar core and suppressing differential rotation as the star evolves, which so far remains largely undetermined (9).

A likely candidate to account for this efficient angular momentum transport is of course stellar magnetism (11–13). Challenging to detect, stellar magnetic fields sometimes manifest themselves through spectacular effects on the plasma flow, as they collimate jets (14) or power stellar flares (15). Even though the intricacies of their dynamical coupling with stellar plasma flows are still essentially unknown, their attempted parametrization in stellar radiative zone models has been shown to crucially modify the predicted mass loss, rotation rate and transport of chemical elements in intermediate mass (16) or massive stars (17–19, 27), showing the need for improved understanding of stellar magnetism. Mixing enhancement by magnetic fields in radiative zones also has important consequences for constraining the star brightness and lifetime, as it can favour the transport of hydrogen fuel toward the core and thus delay the end of the fusion process. Yet, two theoretical problems immediately arise. Firstly, magnetic fields are notoriously difficult to observe in deep stellar layers, which leaves little hope to probe the radiative core of low-mass stars, whereas massive and intermediate-mass stars (whose radiative zone is conveniently close to the surface) are not often known to harbor magnetic fields: only 10% of these stars exhibit strong (> 100G) and steady dipolar fields. These so-called “fossil fields” are assumed to be remnants of their formation stage. Other massive or intermediate-mass stars either present weak (< 1G), complex and unsteady fields, presumably generated by
dynamo effect (20), or even no fields at all - at least no observable ones. In either case - and this is the second problem -, the mechanism by which a dynamo magnetic field can be generated inside a radiative stellar layer remains unclear.

Indeed, the dynamo instability corresponds to the spontaneous development of an amplification loop, by which poloidal magnetic field is converted into toroidal field and vice versa (21). This conversion is mediated by plasma motions, which must be sufficiently complex and powerful for a magnetic seed field to undergo self-amplification. In the convective zone of low-mass stars for example, the required flow complexity is generally provided by the turbulent buoyant plumes agitating the convective regions (22, 23). But in radiative zones, the existence of dynamo action - and of the resulting magnetic braking - is difficult to account for in the absence of a clearly identified source of hydrodynamic turbulence, which a priori seems to be lacking in stably-stratified regions. Several models have been considered to circumvent this problem of angular momentum transport efficiency (24, 25). So far, the only dynamo model that has been implemented to parametrize the effect of magnetism in radiative stars is the so-called Tayler-Spruit dynamo (26, 28). In this model, magnetic field generation in stably-stratified (radiative) layers relies on (i) the winding of poloidal field into toroidal one by differential rotation (the so-called Ω-effect (21)), and (ii) the destabilization of a strong, toroidal and axisymmetric magnetic field by Tayler instability (29), which regenerates a poloidal field and thus (in theory) closes the dynamo loop initiated by differential rotation. Unfortunately, global numerical simulations have consistently failed so far in exhibiting Tayler-Spruit dynamos, casting doubt on whether the simplifications made in Tayler-Spruit theory are likely to fail once turbulence is reinstated (30), and whether there exists at all a dynamo mechanism that could operate in a stratified, hydrodynamically stable stellar layer. It is the aim of the present paper to numerically demonstrate how a hidden magnetic field can build up through dynamo instability, trigger magnetohydrodynamic turbulence and achieve efficient angular momentum transport in a radiative
Results  We model a radiative stellar layer by considering the swirling flow of an electrically conducting fluid (with electrical conductivity $\sigma$, density $\rho$, thermal diffusivity $\kappa$ and kinematic viscosity $\nu$) between two coaxial, spherical shells of radius $r_i$ and $r_o$ spinning at different rates. The intensity of the differential rotation is controlled by the dimensionless Rossby number $Ro = \Delta \Omega / \Omega$, where $\Omega$ (resp. $\Omega + \Delta \Omega$) is the angular velocity of the outer (resp. inner) shell. Stable stratification is achieved inside the fluid by means of a prescribed temperature difference $\Delta T$ between the inner and outer shells, and we focus here on a flow regime where stratification effects remain comparable to the effect of shear. More specifically, the ratio $N/\Omega$ between the Brunt-Väisälä frequency (which quantifies the stratification intensity, $N = (\alpha g \Delta T / (r_o - r_i))^{1/2}$ and the rotation rate $\Omega$ of the star is comprised between 0.1 and 50. The physical variables, governing equations and model parameters are presented in supplementary material.

When the differential rotation across the radiative zone is weak ($Ro < 0.39$), the flow is stable, axisymmetric and all velocity perturbations decay away rapidly. The rotational invariance of the flow is broken only for steeper rotation profiles ($Ro > Ro_{c,1} = 0.39$), where the destabilization of a free shear layer (31) generates a non-axisymmetric azimuthal velocity mode. For this particular intensity of stratification and global rotation, small magnetic disturbances are always suppressed by ohmic diffusion as long as $Ro < 0.78$: here the shear instability is not vigorous enough to generate a dynamo field. For larger shear ($Ro > Ro_{c,2} = 0.78$) however, weak magnetic seed fields undergo exponential amplification and saturate to a very high magnetic state. The bifurcation diagram in Figure[1] shows the remarkable behavior of this new dynamo branch: once the strong magnetic field generated by steep rotation profiles has set in, it can be maintained even when the shear rate is decreased down to $Ro \sim 0.19$, i.e. below the onset of hydrodynamic instability (black diamonds). Note that in the radiative zone modeled here, the
difference of spinning rates between the inner and outer shells is fixed as a simulation parameter \((R_o)\). This can be viewed as a way to focus only on a short period of the star’s life, during which the processes occurring in the bulk flow do not immediately affect the outermost layers. This restriction does not apply to a real radiative zone however, where the rotation profile could, eventually, entirely flatten in time. The following scenario therefore emerges: toward the end of the main sequence, the differential rotation across the radiative zone is large enough (high \(R_o\)) for extremely weak magnetic seed fields to be amplified by dynamo action. As shown below, this dynamo induces efficient outward transport of angular momentum, gradually flattening the rotation profile (i.e. decreasing the effective \(R_o\) number) as the star evolves. The magnetic field dynamically adjusts to the smoother rotation profile and modifies the flow so as to sustain the turbulent motions on which it feeds, thus following the trajectory indicated by the red arrow in Figure 1.

To understand the mechanisms involved in this subcritical dynamo, Figure 2 shows time series of the magnetic field amplitude normalized by rotation effects (the so-called Elsasser number \(\Lambda\), see Methods in Supplementary Material) for a steep rotation profile \((R_o = 0.79)\) and for various ratios of the fluid’s molecular to magnetic diffusivities (referred to as the magnetic Prandtl number \(P_m\)). The first exponential stage corresponds to a kinematic process, where the shear instability amplifies a laminar, axisymmetric toroidal field. This dynamo shares some similarities with a solution previously reported in (32) for an unstratified spherical Couette flow, and seems to be relatively unimportant for the angular momentum transport: for the larger values of the plasma magnetic plasma diffusivity shown in Figure 2 (here \(P_m < 0.5\)), this shear-induced dynamo saturates with relatively weak magnetic fields \((\Lambda < 1)\), and leaves the rotation profile of the star essentially unchanged. Importantly, what happens next appears to depend of the amplitude reached by the magnetic field during the amplification process. To analyse this with global simulations, varying the Prandtl number provides a convenient way of tuning
the saturation amplitude of this first, shear-driven dynamo without changing any of the flow properties. Our simulations show that, every time the toroidal field exceeds the typical transition value $\Lambda_0 \sim 1$ (dashed line in Figure 2), a secondary instability is triggered: for $Pm \geq 0.5$, the exponential growth becomes suddenly steeper; the magnetic field amplitude rapidly gains nearly two orders of magnitude, and finally stabilizes to its saturation amplitude. The inset in Figure 2 shows the kinetic energy contained in the azimuthal wavenumbers $m = 1$ to $m = 6$ in the case $Pm = 1$. Before the secondary growth, the velocity field is laminar, mostly axisymmetric, with a leading $m = 1$ component generating a periodic oscillation of the energy. As the magnetic field reaches $\Lambda = \Lambda_0$, most of the non-axisymmetric components increase and the time series of the kinetic energy become chaotic, illustrating the close interplay between the magnetic instability and the transition to turbulence in the radiative zone.

The snapshots shown in Figure 3 before and after the onset of secondary growth clearly exemplify the destabilizing effect of this magnetic field on the flow structure: the velocity field before is essentially laminar, and the azimuthal magnetic field exhibits a laminar, axisymmetric structure both in the equatorial and meridional planes. The time at which secondary growth sets in precisely corresponds to the non-axisymmetric destabilization of the toroidal magnetic field: after this time, the magnetic field has become strongly chaotic, and exhibits a spiraling configuration with significant small scale fluctuations. The corresponding velocity field is now highly turbulent, especially in the inner regions of the star. Most importantly, this transition to turbulent flow motions also results in noticeably suppressing differential rotation across the fluid, as shown by the flattening of the rotation profile in Figure 3(b). (The movie provided as supplementary material further illustrates this process of toroidal field destabilization and the smoothing of the rotation profile as the dynamo builds up.)

The dynamo identified here presents some striking similarities with the Tayler-Spruit (TS) mechanism (28) predicted nearly 20 years ago. Firstly, this dynamo feeds on the interaction of
a large-scale, toroidal magnetic field with differential rotation: the observed fields are characterized by a strongly dominant axisymmetric, toroidal component, containing more than 80% of the magnetic energy. Secondly, the radial scale typically displayed by magnetic structures is small compared to the azimuthal one, as shown by Figure 3. Thirdly, this dynamo is markedly sensitive to the amplitude of the axisymmetric azimuthal field: just as TS dynamos require a finite-amplitude, axisymmetric, toroidal magnetic field to trigger the Tayler instability, our simulations indicate the existence of a critical value of the azimuthal magnetic field above which the dynamo is suddenly amplified and turbulence is triggered. More specifically, the arrow in Figure 3(a) marks the time of the sudden, secondary amplification: as also shown by the movie provided in supplementary material, this coincides with the time where the maximum amplitude of the axisymmetric component of the azimuthal magnetic field $\vec{B}_\phi$ exceeds the local stability threshold $B^c_\phi$ of Tayler instability in the presence of thermal diffusion effects, in excellent agreement with the theoretical prediction (see e.g. (28)).

On the other hand, the new dynamo described here also exhibits a few major differences with the TS dynamo model. In Spruit’s model, the azimuthal wavenumber spectrum of the instability-generated field is mostly peaked on $m = 1$, whereas the transition reported here is a turbulent one: because of the high Reynolds numbers achieved here, many wavenumbers are excited simultaneously as soon as the onset of Tayler instability is reached (see inset (b) of Fig.2; see also the movie in supplementary material). Note that laboratory investigations (33) of the Tayler instability also reported some azimuthal, magnetic structure more complicated than a single $m = 1$ mode. This somehow resolves a paradox on the Tayler-Spruit dynamo pointed out first by (30), according to which a pure $m = 1$ non-axisymmetric induced field would not be sufficient to regenerate the $m = 0$ toroidal field required to maintain the instability. Indeed, our simulations rather suggest that some type of fluctuations-based TS dynamo is at play here, in which the axisymmetric field is replenished by the mean electromotive force $\langle u \times b \rangle$. Moreover,
(28) relies on the assumption that the Brunt-Väisälä frequency $N$ is much higher than the star rotation rate $\Omega$ (which allows for the so-called shellular approximation, i.e. the assumption that the composition and specific angular momentum only depend on spherical radius). The dynamo reported here does not require such an assumption, as it is observed for values down to $N/\Omega \sim 0.1$. Yet, although the present dynamo mechanisms certainly shows some robustness with respect to the value of the ratio $N/\Omega$, it still requires minimal stratification as no such (TS-like) dynamo was found for $N/\Omega < 0.1$. The saturation mechanism may also be influenced by the strong turbulent dissipation generated by unstable magnetic perturbations, following a scenario recently proposed (35). Note also that, whereas in (28) the finite-amplitude toroidal field is assumed to have grown (linearly) out of a poloidal seed field wound up by differential rotation, in our simulations the primary amplification process prior to subcritical excitation of the TS-like dynamo seems to differ. Indeed, the critical magnetic field for Tayler instability is reached here through some intermediate, weak kinematic dynamo triggered by the differential rotation, which we refer to as weak dynamos in the following. According to self-consistent numerical simulations, many candidates may play this role in stellar interiors (32, 36–38).

As evidenced by the flattening of the rotation profile, the generation of the strong toroidal magnetic field greatly enhances the amount of angular momentum that is transported to the outer regions of the star. This can be quantified by directly measuring the total azimuthal stress $S$ applied on the inner sphere, which includes the contribution of both viscous and magnetic torques. In Figure 4, the dimensionless stress $G = r_i^2 S / \rho \nu^2$ has been systematically computed for a wide range of simulations (with and without magnetic field), where the overall rotation rate (measured by the dimensionless Ekman number $E = v / \Omega r_o^2$) and the stratification of the radiative layer (measured by the Brunt-Väisälä frequency $N = \sqrt{\alpha g \Delta T / (r_o - r_i)}$) were varied. This figure shows a clear separation between weak dynamos, which saturate at $\Lambda < \Lambda_c$, and TS-like dynamos, which correspond to the strong-field solution described above: indeed, the
transport of angular momentum induced by the latter always outweighs that of weak dynamos
(green diamonds) or purely hydrodynamical simulations (black circle). Note however that the
relative enhancement of the total torque (represented by the black arrow in Figure 4) between
hydrodynamic runs and their MHD counterpart is strongly limited by the imposed rotation rates
of the boundaries, which are necessary to prescribe the shear across the fluid domain, but yield
artificial contributions to the viscous torque compared to what would occur in a free stellar layer.
This limitation is however readily overcome: to estimate the transport due to the magnetic field
and compare it to theoretical predictions, it is necessary to compute the azimuthal stress $\mathbf{B}_r \mathbf{B}_\phi / \mu$
exerted on the fluid by the dynamo field only (see Methods in Supplementary material for the
details of the calculation). As shown by the inset of Figure 4, TS-like dynamos are then found
to remarkably scale as $B_r B_\phi / \mu \propto \rho (U_0 \Omega)^{3/2} / N$, or in dimensionless form:

$$G_{mag} = \mathcal{N} \equiv \beta \rho^{5/2} \left( \frac{U_0 \Omega}{N} \right)^{3/2} \frac{r}{\nu^2},$$

(1)

where $U_0$ is the local azimuthal velocity measured in the dynamo region and $\beta \sim 10^{-1}$ is an
adjustable parameter standing for geometrical effects. Interestingly, this scaling law precisely
corresponds to Spruit’s theoretical prediction $B_r B_\phi / \mu \propto \rho \Omega^2 r^2 q^3 \left( \frac{\Omega}{N} \right)^4$ in which the dimen-
sionless differential rotation rate $q$ is expressed as $q \sim k U_0 / \Omega$, where $k = N \sqrt{\mu \rho / B_\phi}$ is the
radial wavenumber at which the Tayler instability takes place (28, 35). By contrast, the inset
of Figure 4 shows that the transport of angular momentum by weak-field dynamos is not at
all described by this scaling law. All these observations further suggest that the strong-field
simulations reported here constitute the first evidence of Tayler-Spruit dynamos. Note that the
use of an effective, turbulent ohmic diffusivity in Spruit’s analysis makes his scaling prediction
particularly relevant for our high-Reynolds simulations, where turbulent fluctuations are likely
to drive the saturation process.
Conclusion  Our simulations may arguably constitute the first numerical evidence of a turbulent radiative dynamo, in which a strong magnetic field can be sustained by dynamo action inside a stably-stratified radiative zone, suppressing differential rotation and inducing significant spin-down of the stellar core as the star evolves away from the main sequence stage. As such, this dynamo provides a plausible mechanism to account for the efficient transport of chemical elements and angular momentum in intermediate mass and massive stars where no convective dynamo is likely to operate. It also provides a possible, additional transport mechanism for the radiative layers of solar-like stars (39) and thus account for the remarkably flat rotation profile of the Sun radiative zone (8). Although this strong-field dynamo is found to share many features with the well-known Tayler-Spruit model, it also exhibits significant differences, and offers several new insights on the possible dynamics of stellar radiative zones. Firstly, this dynamo is found to operate well below the onset of shear instability, and can therefore sustain strong velocity fluctuations even in flow regimes where no hydrodynamic source of turbulence is available. Secondly, the dynamo loop involves the destabilization of multiple small scales rather than that of a single azimuthal $m = 1$ mode, suggesting a saturation mechanism based on turbulent fluctuations. This observation may resolve several of the previously mentioned contradictions about the TS model (30, 34). Note that the scaling law of Figure 4 may eventually change at extreme Reynolds and Ekman numbers. In this regard, it would be interesting to push global numerical simulations as far as possible toward more realistic values and test this hypothesis. Nevertheless, the prediction (1) already provides an interesting new constraint for angular momentum transport in stellar interiors.

It is remarkable that the existence of the strong-field dynamo branch seems extremely robust: for example, the shear instability is not critical to its existence, as it can also be triggered by simply applying a sufficiently strong initial toroidal magnetic field. In addition, it is observed over a wide range of differential rotation and stratification profiles, spanning almost one order
of magnitude in $Ro$ and showing no sign of inhibition at large values of $N/\Omega$. The magnetic and kinetic structures revealed by our simulations should therefore provide new constraints on the dynamics of stellar evolution codes once extrapolated to the relevant parameter regime for stellar interiors. Finally, let us recall that the poloidal component of the dynamo mechanism identified here appears to be extremely weak, and the resulting magnetic fields are therefore essentially toroidal. Consequently, they are also screened by the (comparatively) quasi-insulating interstellar medium, which means that they are barely observable. They are also deeply seated in the star internal layers where intense differential rotation takes place, and restricted to narrow radial scales. The present results therefore provide a physical mechanism by which efficient transport of angular momentum and chemical mixing can occur through hidden dynamo action in stellar interiors where no magnetic fields have been detected so far.

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**Acknowledgments**

This study was granted access to the HPC resources of MesoPSL financed by the Région île-de-France and the project EquipMeso (reference ANR-10-EQPX-29-01) of the programme Investissements d’Avenir supervised by the Agence Nationale pour la Recherche. Numerical simulations were also carried out at the CINES Occigen computing centers (GENCI project A001046698). LP acknowledges financial support from “Programme National de Physique Stellaire” (PNPS) of CNRS/INSU, France. CG acknowledges financial support from the French program ‘JCJC’ managed by Agence Nationale de la Recherche (Grant ANR-19-CE30-0025-01). FM acknowledges financial support from the French program ‘T-ERC’ managed by Agence Nationale de la Recherche (Grant ANR-19-ERC7-0008-01).
Figure 1: Time-averaged magnetic energy density of the saturated dynamo versus the shear rate (Rossby number $Ro$), for $E = 10^{-5}$, $N/\Omega = 1.24$, $Pr = 0.1$ and $Pm = 1$. Empty diamonds indicate linearly unstable solutions from which exponential growth of magnetic field is observed. Full diamonds illustrate the bistability between a purely hydrodynamic solution (lower branch) and a strong toroidal dynamo solution (upper branch).
Figure 2: Time series of the magnetic energy for $E = 10^{-5}$, $N/\Omega = 1.24$, $Pr = 0.1$, $Ro = 0.78$ and various values of the magnetic Prandtl number $Pm = \{0.35; 0.42; 0.5; 1\}$. A secondary instability occurs when the magnetic field exceeds a typical amplitude value $\Lambda_0 \sim 1$ (dashed line). Inset: kinetic energy contained in the azimuthal wavenumbers $m = 1$ to $m = 6$, for the case $Pm = 1$. (Resolution: $nr = 336; l_{\text{max}} = 156; m_{\text{max}} = 56$).
Figure 3: *Top:* Time series of the total kinetic and magnetic energies (a), and radial profiles of the azimuthally-averaged angular velocity $\Omega$ in the equatorial plane (b) for two distinct times, marked as [t1] and [t2] in the time series. *Bottom:* Snapshots of the non-axisymmetric angular velocity (left) and the azimuthal magnetic field (middle), both showed in the equatorial plane, and of the azimuthal magnetic field in the meridional plane (right). (The symbol $\langle \cdot \rangle_\phi$ denotes spatial averaging in the azimuthal direction.) Panel [t1] (resp. panel [t2]) represents these fields before (resp. after) the onset of secondary (Taylor) instability. The associated enhanced transport of angular momentum causes the flattening of the rotation profile (top-right). Parameter values: $E = 10^{-5}$, $N/\Omega = 1.24$, $Pr = 0.1$, $Ro = 0.78$ and $Pm = 1$. Note that the arrow in (a) marks the time where the amplitude of the axisymmetric component of the azimuthal magnetic field $\bar{B}_\phi$ locally exceeds the threshold $B_{c,\phi}$ for Tayler instability, in excellent agreement with the theoretical prediction $B_{c,\phi} \approx 0.03$ for these parameter values (see Eq. 11 in (28)).
Figure 4: Dimensionless torque $G$ exerted on the inner sphere as a function of the dimensionless quantity $N$ (see main text), showing a significant difference in behavior between purely hydrodynamical (empty circles) or weak-dynamos (green diamonds) simulations on the one hand, and strong-field (TS-like) dynamos simulations on the other hand. The inset focuses on the torque exerted by the dynamo field only, shown here for different values of the Ekman number $E$ and compared to Spruit’s theoretical prediction (28). The arrow compares two simulations run with identical control parameters, with and without magnetic fields. (See the Supplementary material for the details of the torque calculation.)