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DIFFERENTIAL ROTATION OF CELESTIAL BODIES AND THE CORIOLIS FORCE

E. F. Babayev[1] *, N. S. Dzhalilov[1]

[1] *Shamakhi Astrophysical Observatory named after N. Tusi, Ministry of Science and Education of the Republic of Azerbaijan, Y.Mammadaliyev Settlement, Shamakhi AZ5626, Azerbaijan*

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ABSTRACT

Differential rotation is a central organising mechanism in rotating planets, stars, and magnetised plasma envelopes. This article treats the problem as a comparative dynamical analysis and asks how latitudinal and radial shear, Coriolis deflection, and wave-mediated angular-momentum transport form a single physical chain across planetary atmospheres, the solar convection zone, and magnetically active stellar interiors. Starting from the momentum equation in a rotating frame, the paper derives the role of the Coriolis term, introduces the Rossby number and the latitudinal beta effect as diagnostic parameters, and relates these quantities to observed solar differential rotation, tachocline shear, solar-like stellar rotation, and Rossby or r-mode oscillations. The analysis shows that differential rotation should not be interpreted simply as a surface rotation law; it is a maintained non-equilibrium state in which Reynolds stresses, baroclinicity, meridional circulation, Lorentz forces, and global waves compete to redistribute angular momentum. The Sun is used as the principal astrophysical case because helioseismology constrains its internal angular velocity profile, while the Earth-atmosphere system provides the clearest geophysical analogue for Coriolis-controlled wave dynamics. A synthesis table is proposed to classify rotating celestial systems according to dominant force balance, expected shear morphology, and wave response. The resulting framework clarifies why Rossby-type modes can appear in both neutral planetary fluids and magnetised stellar plasmas, although their restoring mechanisms and observational tracers differ.

Key words: differential rotation – Coriolis force –Rossby number – Rossby waves – solar rotation – tachocline – helioseismology – stellar convection – angular momentum transport.

1 INTRODUCTION

Rotation enters astrophysical and geophysical fluid dynamics not as a secondary kinematic detail but as a force-organising constraint. Once a body rotates rapidly enough for the Coriolis acceleration to be comparable with inertial acceleration, the motion of gas, plasma, atmosphere, or ocean no longer follows the intuition of a non-rotating frame. The flow tends to align with the rotation axis, angular momentum becomes redistributed by correlated velocity fluctuations, and large-scale waves appear because the effective vorticity changes with latitude. These effects are especially important in the Sun and in solar-type stars, where convection, magnetic fields, and rotation jointly determine the observed pattern of differential rotation and the operation of magnetic dynamos (Tassoul 1978; Thompson et al. 2003; Miesch 2005; Miesch and Toomre 2009).

The term differential rotation describes the situation in which angular velocity is not spatially uniform. It may vary with latitude, radius, depth, or time. The solar photosphere provides the classical example: equatorial regions rotate faster than higher latitudes, and helioseismic inversions show that this surface pattern is connected to a structured internal rotation profile rather than to a shallow surface phenomenon alone (Schou et al. 1998; Howe 2009). In planetary atmospheres the same general issue appears in a different form. The solid planet may have a well-defined rotation rate, but the atmosphere and ocean organise themselves into jets, cells, gyres, and planetary waves because the Coriolis parameter varies with latitude (Holton and Hakim 2012; Vallis 2017). Thus, the physics of differential rotation links apparently separate systems: stellar convection zones, planetary atmospheres, giant-planet envelopes, accretion flows, and magnetised plasma layers.

The scientific difficulty is that differential rotation is both a cause and a consequence of angular-momentum transport. Shear can amplify magnetic field by the omega effect, but magnetic stresses can feed back on shear. Convection can generate Reynolds stresses that maintain latitudinal angular-velocity gradients, but the Coriolis force modifies the convec-

* E-mail: bemin4610@gmail.com

tive cells that generate those stresses. Rossby waves can redistribute angular momentum, but their propagation depends on the very rotation profile that they help to alter. A coherent treatment therefore requires more than a descriptive list of examples. It requires an explicit chain of dynamical reasoning from the rotating-frame momentum equation to the observed morphology of planetary and stellar flows.

A related extension is provided by the epsilon-mechanism interpretation of solar variability discussed by Dzhalilov and Staude (2005). In that view, radiation energy generated in the nuclear core may interact with the differentially rotating central solar region and excite Rossby-type vortical structures. If such vortices locally disturb the efficiency of nuclear energy generation, the solar luminosity integrated over the visible disk may acquire a weak quasi-periodic modulation. This idea is not treated here as an established observational result; rather, it is used as a motivating hypothesis connecting internal rotation, Rossby-type dynamics, nuclear-fusion sensitivity, and possible long-timescale solar forcing relevant to climate-variability models.

The aim of this article is to provide that chain. The paper has four specific objectives. First, it formulates the Coriolis force, Rossby number, beta effect, and differential-rotation measures in a common notation. Second, it interprets solar differential rotation as a maintained dynamical state rather than a static observational fact. Third, it compares planetary Rossby waves with solar Rossby-like modes and stellar r-modes, emphasising both the shared vorticity principle and the differences introduced by stratification and magnetism. Fourth, it proposes a compact classification of rotating celestial bodies according to dominant force balance, expected shear structure, and wave response. In this sense the contribution of the paper is analytical synthesis: it reorganises established observational and theoretical material into a comparative framework that can be used to interpret rotating celestial systems without treating each system in isolation.

2 DYNAMICAL FORMULATION IN A ROTATING FRAME

Consider a fluid element described in a reference frame rotating with angular velocity $\mathbf{\Omega}$. The momentum equation may be written as

$$\begin{aligned}\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right) = & -\nabla p+\rho\mathbf{g}-2\rho\mathbf{\Omega}\times\mathbf{u} \\ & -\rho\mathbf{\Omega}\times(\mathbf{\Omega}\times\mathbf{r})+\mathbf{F}_{\rm visc}+\mathbf{F}_{\rm mag}.\end{aligned} \tag{1}$$

where ρ is density, $\mathbf{u}$ is velocity in the rotating frame, p is pressure, $\mathbf{g}$ is gravity, $\mathbf{F}_{\rm visc}$ denotes viscous or turbulent stresses, and $\mathbf{F}_{\rm mag}$ denotes the Lorentz force when the medium is conducting. The term $-2\rho\mathbf{\Omega}\times\mathbf{u}$ is the Coriolis force per unit volume. It does no mechanical work because it is perpendicular to the instantaneous velocity, yet it changes the direction of motion and thereby reorganises circulation, convection, and wave propagation.

A useful nondimensional measure of rotational control is the Rossby number,

$$Ro=\frac{U}{2\Omega L}, \tag{2}$$

where U and L are characteristic velocity and length scales. When $Ro \ll 1$, Coriolis effects dominate inertial advection and the flow tends to become rotationally constrained. When $Ro \gtrsim 1$, inertial and buoyant motions can cross the rotational constraint more freely. In stellar convection zones this number is not uniform: near-surface granulation, deep convection, and global meridional circulation occupy different dynamical regimes. This is one reason why a star can exhibit near-surface shear, deeper conical rotation contours, and tachocline shear in the same object (Miesch 2005; Miesch and Toomre 2009).

Differential rotation may be described through an angular-velocity field $\Omega(r,\theta,t)$, where r is radius and θ is colatitude. A commonly used surface representation is

$$\Omega(\lambda)=A+B\sin^2\lambda+C\sin^4\lambda, \tag{3}$$

where λ is latitude and the coefficients express equatorial rotation and latitudinal shear. For the solar interior, however, Eq. (3) is insufficient because helioseismology reveals radial as well as latitudinal gradients. A more physically meaningful diagnostic is the relative shear,

$$\alpha=\frac{\Omega_{\rm eq}-\Omega_{\rm pole}}{\Omega_{\rm eq}}, \tag{4}$$

combined with radial gradients such as $\partial\Omega/\partial r$ across the near-surface shear layer and the tachocline.

The beta effect is the wave counterpart of the same rotational geometry. On a spherical body the vertical component of planetary vorticity changes with latitude. In a local beta-plane approximation,

$$f=f_0+\beta y, \qquad \beta=\frac{2\Omega\cos\phi_0}{R}, \tag{5}$$

where $f=2\Omega\sin\phi$ is the Coriolis parameter, R is the radius, and ϕ_0 is a reference latitude. This gradient supplies the restoring mechanism for Rossby waves in atmospheres and oceans (Rossby 1939; Gill 1982; Pedlosky 1987; Vallis 2017). In stars, analogous global r-modes arise because rotating spherical fluids possess vorticity-conserving oscillations whose dynamics are modified by stratification, compressibility, differential rotation, and magnetic fields (Papaloizou and Pringle 1978; Zaqarashvili 2021; McIntosh et al. 2017; Loptien et al. 2018).

3 DIFFERENTIAL ROTATION AS AN ANGULAR-MOMENTUM TRANSPORT PROBLEM

A uniformly rotating self-gravitating body is dynamically simple only in an idealised limit. Real celestial bodies contain

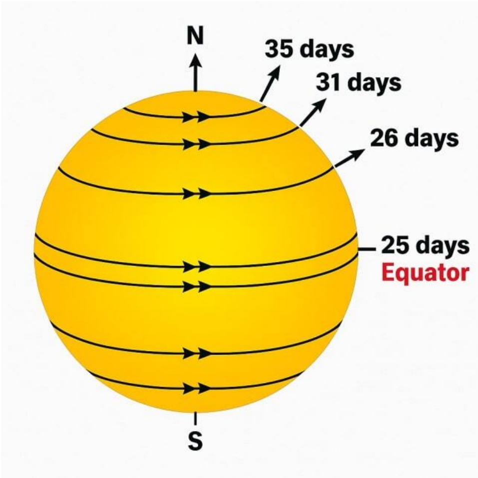

Figure 1. Schematic representation of solar differential rotation. The equatorial region rotates faster than high latitudes, producing a latitude-dependent angular velocity that is central to solar dynamo models. *Source:* Authors' schematic based on Schou et al. (1998), Thompson et al. (2003), and Howe (2009).

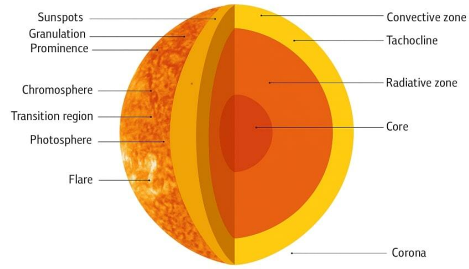

Figure 2. Illustrative internal structure of the Sun and its rotation profile. The radiative interior, convection zone, near-surface layers, and tachocline participate differently in the redistribution of angular momentum. *Source:* Authors' schematic based on Schou et al. (1998), Thompson et al. (2003), and Howe (2009).

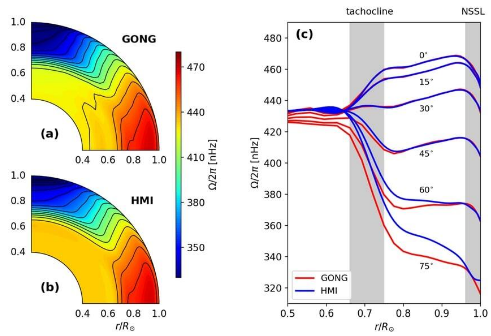

Figure 3. Conceptual view of the tachocline as a shear interface between the differentially rotating convection zone and the more uniformly rotating radiative interior. This layer is widely regarded as important for solar magnetic-field generation. *Source:* Authors' schematic based on Thompson et al. (2003) and Charbonneau (2010).

turbulence, stratification, convection, radiative zones, magnetic stresses, and boundary layers. The observed angular velocity is therefore the outcome of transport processes rather than an arbitrary profile. In a rotating convection zone, correlations such as $\langle u_r u_\phi \rangle$ and $\langle u_\theta u_\phi \rangle$ transport angular momentum. These Reynolds stresses compete with meridional circulation and turbulent diffusion. When the medium is ionised, Maxwell stresses add another channel for angular-momentum redistribution.

The Sun illustrates the problem with exceptional clarity because the internal rotation profile is observationally constrained. Helioseismic measurements show that the solar convection zone rotates differentially, that the radiative interior is closer to solid-body rotation, and that a sharp transition occurs near the base of the convection zone in the tachocline (Schou et al. 1998; Thompson et al. 2003; Howe 2009). The tachocline is important not merely as a structural boundary but as a shear layer in which toroidal magnetic field can be produced from poloidal field. This links differential rotation directly to dynamo theory (Parker 1955; Charbonneau 2010).

The qualitative statement that the solar equator rotates faster than the poles is therefore only the visible endpoint of a deeper dynamical balance. In the bulk of the convection zone, rotating convection tends to generate angular-momentum transport that favours solar-like differential rotation under suitable Rossby-number conditions. In the tachocline, radial shear and stable stratification confine strong gradients to a thin region. Near the photosphere, thermal stratification and small-scale convection contribute to a separate near-surface shear layer. A complete interpretation must therefore combine latitudinal shear, radial shear, and temporal modulation.

The role of the Coriolis force is indirect but decisive. Rising and sinking convective parcels are deflected, producing tilted convective structures. These tilts create systematic correlations in velocity fluctuations, which then transport angular momentum. If rotation is weak relative to convection, the correlation is reduced and the differential rotation can change sign or become less coherent. Numerical simulations and stellar observations suggest that the transition between solar-like and anti-solar differential rotation is controlled substantially by the convective Rossby number, although details depend on luminosity, mass, age, and magnetic feedback (Gastine et al. 2014; Brun and Browning 2017).

4 CORIOLIS FORCE IN PLANETARY AND STELLAR CONTEXTS

On Earth, the Coriolis force is most familiar through the deflection of winds and ocean currents. In the Northern Hemisphere large-scale horizontal motion is deflected to the right of its direction of travel; in the Southern Hemisphere it is deflected to the left. This rule is only a surface manifestation of a more general vorticity constraint. Geostrophic balance, in which pressure-gradient force and Coriolis force approximately balance, explains the prevalence of large-scale atmospheric flows parallel to isobars. Departures from this balance

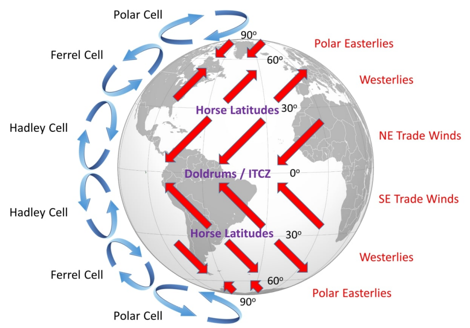

Figure 4. Schematic illustration of Coriolis deflection in a rotating planetary atmosphere. The same mathematical term that organises atmospheric circulation also affects plasma motion in rotating stellar envelopes, although the force balance differs in magnetised plasma. *Source:* Authors' schematic based on Holton and Hakim (2012) and Vallis (2017).

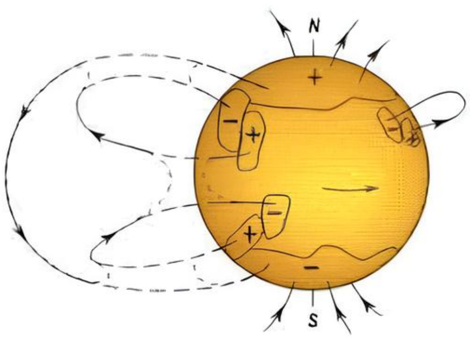

Figure 5. Schematic representation of rotational deflection in solar plasma motion. Convective upflows and downflows are deflected by rotation, contributing to helicity and angular-momentum transport. *Source:* Authors' schematic based on Stix (2002), Charbonneau (2010), and Brun and Browning (2017).

allow vertical motion, cyclogenesis, jet-stream meanders, and wave propagation (Holton and Hakim 2012; Vallis 2017).

The solar case is less intuitive because the moving medium is conducting plasma rather than neutral air or water. Nevertheless, the Coriolis term in Eq. (1) remains present. It deflects convective motions, contributes to helicity, influences meridional circulation, and helps determine the sign and strength of Reynolds stresses. In mean-field dynamo language, rotationally influenced convection contributes to the generation of poloidal field from toroidal field, while differential rotation contributes to toroidal-field amplification from poloidal field. The Coriolis force therefore participates in the dynamo indirectly by shaping the geometry and statistical properties of turbulence (Stix 2002; Charbonneau 2010; Brun and Browning 2017).

A useful way to compare Earth and the Sun is not to ask whether their flows look the same; they plainly do not. The appropriate question is whether their governing balances contain homologous terms. Earth-atmosphere dynamics are often approximated by hydrostatic and geostrophic balances with moist thermodynamics, while solar convection involves

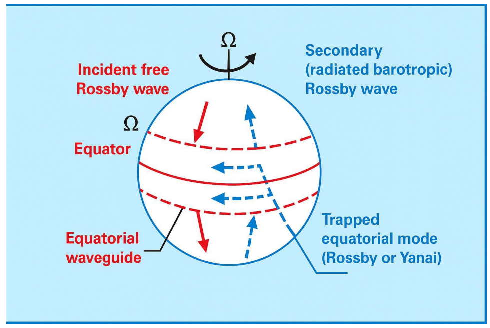

Figure 6. Schematic geometry of Rossby-wave propagation. Latitudinal variation of planetary vorticity provides the restoring mechanism and leads to characteristic retrograde phase propagation. *Source:* Authors' schematic based on Rossby (1939), Gill (1982), and Vallis (2017).

compressibility, ionisation, radiative transport, and magnetohydrodynamics. Yet both systems contain a rotating-frame vorticity equation in which planetary or stellar rotation supplies a preferred axis and a latitude-dependent background vorticity. This shared structure explains why Rossby-type phenomena appear in both systems despite different material properties.

5 ROSSBY WAVES, R-MODES, AND THE BETA EFFECT

Rossby waves arise because a displaced fluid element must conserve potential vorticity while moving across a background vorticity gradient. In a simple barotropic beta-plane model, the dispersion relation is

$$\omega = Uk - \frac{\beta k}{k^2 + l^2}, \tag{6}$$

where ω is angular frequency, U is background zonal flow, and k and l are zonal and meridional wavenumbers. The intrinsic phase propagation is westward relative to the mean flow. This property underlies the slow meandering of planetary waves and the redistribution of angular momentum in atmospheres and oceans (Rossby 1939; Gill 1982; Pedlosky 1987; Vallis 2017).

In stars, the equivalent family of oscillations is usually discussed as r-modes or Rossby-like waves. In a uniformly rotating, inviscid spherical shell, the simplest sectoral r-mode frequencies in the co-rotating frame scale with rotation as

$$\omega_{\rm co} \simeq -\frac{2m\Omega}{\ell(\ell+1)}, \tag{7}$$

where ℓ and m are spherical harmonic degree and azimuthal order. Real solar modes deviate from this simple relation because the Sun is differentially rotating, stratified, magnetised, and turbulent. Nevertheless, the negative sign captures the essential retrograde character of Rossby-like modes in the rotating frame.

Observational evidence for solar Rossby-like waves has developed through tracking of photospheric and coronal tracers.

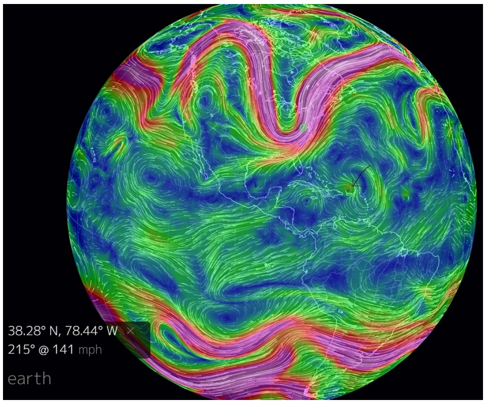

Figure 7. Planetary-scale wave organisation in a rotating atmosphere or ocean. Such patterns provide the geophysical analogue for interpreting Rossby-like behaviour in rotating stellar envelopes. *Source:* Authors' schematic based on Gill (1982), Holton and Hakim (2012), and Vallis (2017).

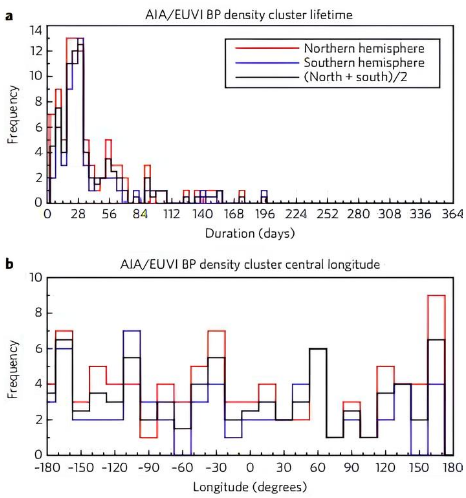

Figure 8. Coronal bright points used as tracers of large-scale solar wave patterns. Tracking magnetic tracers across longitude and latitude allows Rossby-like oscillations to be inferred from coherent retrograde structures. *Source:* Authors' schematic based on McIntosh et al. (2017) and Loptien et al. (2018).

The detection of large-scale Rossby-like waves using coronal bright points observed by SDO and STEREO provided a direct connection between solar magnetic structures and global rotating-fluid dynamics (McIntosh et al. 2017). Subsequent helioseismic and feature-tracking studies have strengthened the view that global-scale retrograde modes are a real component of solar dynamics (Loptien et al. 2018). These observations are significant because they suggest that angular-momentum redistribution in the Sun is partly wave-mediated, not only turbulence-mediated.

The conceptual bridge between planetary Rossby waves and solar r-modes must be drawn carefully. In a neutral planetary atmosphere, the primary restoring mechanism is the conservation of potential vorticity in the presence of the beta effect and stratification. In the Sun, the same rotational geometry is present, but magnetic tension, turbulent stresses, and radial shear modify both the dispersion and damping of modes. Hence the phrase Rossby-like is physically appropriate: the modes are homologous in their vorticity foundation but not identical in their full force balance.

6 COMPARATIVE CLASSIFICATION OF ROTATING CELESTIAL BODIES

The following synthesis table summarises the analytical framework proposed here. It classifies systems not by appearance but by dominant force balance and expected dynamical response. The classification is necessarily simplified, but it makes explicit what is often implicit in descriptive treatments of differential rotation.

The table yields three interpretive conclusions. First, differential rotation is best understood as a transport problem. The visible angular-velocity profile is an outcome of competing fluxes of angular momentum. Second, the Coriolis force is not merely a deflection term; by shaping the correlations of turbulent motion it controls how angular momentum is transported. Third, Rossby-type waves are a natural response of rotating spherical fluids and plasmas because latitude-dependent background vorticity is geometrically unavoidable on a rotating sphere.

7 IMPLICATIONS FOR SOLAR AND STELLAR ACTIVITY

Differential rotation is essential to solar and stellar magnetic activity because it converts poloidal magnetic field into toroidal field through shear. In the Sun, this process is associated with the 11-year sunspot cycle and the 22-year magnetic cycle. The tachocline has traditionally been emphasised as a storage and amplification region, although modern dynamo models also recognise the importance of distributed convection-zone processes and near-surface shear (Parker 1955; Charbonneau 2010; Brun and Browning 2017).

Rossby-like waves add another layer to this picture. If global modes redistribute angular momentum or modulate the emergence of magnetic flux, they may help explain quasi-periodic patterns in solar activity. The 90–200 day periodicities reported in coronal bright-point studies are not a replacement for the dynamo cycle, but they may represent an intermediate timescale on which rotation, magnetic fields, and wave dynamics interact (McIntosh et al. 2017). This suggests that the solar cycle should not be interpreted only as a mean-field magnetic oscillator; it is also embedded in a spectrum of rotating-fluid modes.

For stars beyond the Sun, the problem is harder because internal rotation profiles are not normally resolved. Surface spot modulation, chromospheric activity, and asteroseismic rotational splittings provide partial constraints. The same framework remains useful, however, because it predicts that stars with different Rossby regimes should display different relationships among rotation rate, differential shear, magnetic activity, and global oscillations. Rapid rotators are ex-

Table 1. Comparative dynamical regimes of rotating celestial systems.

System class	Dominant balance	Differential-rotation morphology	Wave response	Principal diagnostic
Terrestrial atmospheres and oceans	Pressure gradient, Coriolis force, stratification, friction	Zonal jets and gyres relative to solid-body rotation	Rossby waves and jet meanders	Wind, pressure, temperature, sea-surface height
Giant-planet atmospheres	Rotation, convection, stratification, internal heat flux	Strong banded zonal jets	Planetary waves, vortices, normal modes	Cloud tracking and thermal emission
Solar convection zone	Rotating convection, Reynolds stress, meridional flow, Lorentz feedback	Equator-fast latitudinal shear with radial structure	Rossby-like modes, inertial waves, torsional oscillations	Helioseismology, Doppler rotation, magnetic tracers
Tachocline and stable stellar interfaces	Shear, stratification, magnetic tension, thermal wind balance	Thin radial shear layer	Magneto-Rossby and shear-modified modes	Helioseismic inversion and activity-cycle modulation
Rapidly rotating solar-like stars	Strong rotational constraint and magnetic feedback	Solar-like or anti-solar shear depending on Rossby regime	Global r-modes and activity-linked modulation	Asteroseismology, spot modulation, activity indicators

pected to be more strongly rotationally constrained; slowly rotating convective stars may approach regimes in which anti-solar differential rotation becomes possible (Gastine et al. 2014; Brun and Browning 2017).

8 DISCUSSION

The central result of this article is a conceptual reclassification of differential rotation. Rather than treating the Coriolis force, Rossby waves, solar rotation, and stellar dynamos as separate topics, the paper places them in a single causal sequence. Rotation introduces Coriolis acceleration; Coriolis acceleration constrains convection and circulation; constrained flows transport angular momentum anisotropically; anisotropic transport maintains differential rotation; differential rotation and latitude-dependent vorticity support global waves; waves and magnetic stresses feed back on the angular-momentum budget.

This sequence also clarifies the limits of analogy. The Earth and the Sun are not dynamically identical. The Earth has a solid lower boundary, a thin atmosphere, oceans, moisture, topography, and comparatively weak ionisation. The Sun has a deep compressible convection zone, no solid surface, strong magnetic feedback, and a radiative interior. Nevertheless, both systems are rotating spherical fluids in which vorticity conservation and Coriolis deflection structure large-scale motion. The analogy is therefore not morphological but dynamical.

The framework has practical implications for future work. Observationally, simultaneous use of helioseismic rotation inversions, magnetic tracers, and coronal bright-point tracking can separate advection by mean flows from true wave propagation. Theoretically, models should report not only the resulting angular-velocity maps but also the associated angular-momentum flux decomposition. For stellar applications, the Rossby number should be treated as a depth-dependent and process-dependent diagnostic rather than as a single global number derived from rotation period alone.

9 CONCLUSIONS

This paper examines differential rotation and the Coriolis force as an analytical synthesis. The main conclusions are as follows:

(i) Differential rotation is a maintained non-equilibrium state produced by angular-momentum transport, not merely an observed latitude-dependent rotation law.

(ii) The Coriolis force controls differential rotation indirectly by shaping convective tilts, Reynolds stresses, meridional circulation, and global vorticity balance.

(iii) The Sun is the key astrophysical reference case because helioseismology demonstrates radial and latitudinal internal rotation structure, including the tachocline.

(iv) Rossby waves in planetary atmospheres and Rossby-like r-modes in stellar plasmas share a vorticity foundation, but solar and stellar cases are modified by magnetic fields, stratification, shear, and turbulence.

(v) A comparative regime classification based on force balance, shear morphology, and wave response provides a more original and analytically useful structure than a descriptive listing of known examples.

(vi) The epsilon-mechanism hypothesis adds a further interpretive possibility: Rossby-type vortices generated in differentially rotating inner solar layers may modulate the nuclear-fusion rate and, consequently, the integrated solar luminosity on quasi-periodic timescales. In this limited sense, the mechanism may offer a new theoretical link between internal solar dynamics and climate-variability modelling (Dzhalilov and Staude 2005).

The contribution of this study is not the presentation of new observational data, but the construction of an integrated dynamical framework that links differential rotation, Coriolis forcing, and Rossby-type wave dynamics across celestial bodies.

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